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Prospects for Mineral Resource Assessments on Public Lands: Proceedings of the Leesburg Workshop

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Prospects for Mineral Resource Assessments on Public Lands: Proceedings of the Leesburg Workshop

Edited by Simon M. Cargill *and* Steven B. Green

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PREFACE

Modern geological surveys pursue a wide spectrum of research activities in the earth sciences. From the beginning, however, one of the core tasks of any national geological survey has been the assessment and evaluation of its nation's mineral and fuel resources. The methods by which such assessments are carried out have become more sophisticated over time, in keeping with advancing geoscientific knowledge and the development and application of new concepts and technologies. However, the basic objectives of such work have changed little, and the fundamental goal remains the construction of the best possible base of information on the nature, distribution and economic potential of the resources within a nation's landmass and its offshore jurisdictions.

In recent decades, much of the attention and emphasis in resource assessment has been directed at fuel resources, particularly petroleum and natural gas. The reasons for this emphasis have been glaringly obvious, as Western nations struggle to introduce policies and strategies adapted to the new economic realities triggered by the oil crises of the mid-1970's. Mineral resources in general have not occupied the same spotlight on the world's economic stage. Nevertheless, for a variety of strategic, industrial, and planning purposes, the assessment of metallic and nonmetallic mineral resources remains a priority of both the U.S. Geological Survey (USGS) and the Geological Survey of Canada (GSC). Thus, when staff of our two agencies first proposed a discussion forum on the current state of the art in mineral resource assessment and the probable paths of future developments in this area, the time seemed right. The Leesburg Workshop was the result.

For some time now, the USGS and the GSC have had in place a Memorandum of Understanding to facilitate cooperative research work between the two agencies, and a number of collaborative ventures have been undertaken. This report on the proceedings of the Leesburg Workshop is a product of this collaborative process; we hope that many such joint activities will follow in the future.

RAPrice

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Director General
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INTRODUCTION

The Leesburg Workshop was designed to review the current status of methods for metallic mineral resource assessment. The workshop was convened under the Memorandum of Understanding for cooperative research between the U.S. Geological Survey (USGS) and the Geological Survey of Canada (GSC). Held September 23 to 29, 1985, at the Xerox International Center for Training and Management Development near Leesburg, Va., the workshop drew about 125 invited participants representing U.S. and Canadian Federal, State, and Provincial agencies, as well as delegates from U.S. and Canadian industry and universities (see app. 1).

Both the USGS and the GSC have devoted considerable time, effort, and resources over the past decade or more to resource assessment work. The result has been the development of methodologies and programs for conducting the required assessments on a formal basis. Although the approach to this work in both agencies has been generally similar, differences linked to the different political and policy requirements of the two agencies do exist. Because of these very commonalities and differences, it was considered instructive for staff of the two agencies, along with other interested participants, to meet and compare notes. The Leesburg Workshop was the result.

Resource assessments are conducted for a variety of reasons. In many cases, however, the driving force is a policy need, often connected with land use planning. In the United States this development is historically linked to the Wilderness Act of 1968, which directs the U.S. Geological Survey and the U.S. Bureau of Mines to make mineral surveys of wilderness and primitive areas within the United States. This mandate, coupled with subsequent legislation such as the Alaska Native Claims Settlement Act of 1971, led to the establishment of USGS programs such as the Alaska Mineral Resource Assessment Program (AMRAP) and the Conterminuous United States Mineral Assessment Program (CUSMAP).

In Canada, the experience generally has been less formalized, and large integrated assessment programs such as AMRAP and CUSMAP have not been introduced. However, beginning in the 1970's with the establishment of a formal requirement for annual assessments of Canada's uranium resources under the Atomic Energy Control Act, the GSC has been increasingly involved in resource assessment work. Over the last 10 years, the GSC has carried out a series of resource assessment projects in the Northwest Territories and the Yukon Territory principally for land use planning in connection with the establishment of national parks and other conservation areas and for providing background resource information for native peoples' land claim negotiations. As it has in the United States, resource assessment in Canada is becoming a more formalized and systematic process.

The organizers of the Leesburg Workshop had three purposes in mind:

1. To generate discussion on the mechanisms and impacts of resource assessment results on resource management policy and land use planning.
2. To document methods currently used in resource assessment, drawing on appropriate case histories.
3. To consider future trends in resource assessment methods, particularly quantitative.

These three objectives were first addressed in the plenary sessions held during the first 2 days of the workshop. Session I (Government Role in Policy Formulation) consisted of invited papers on the roles of various U.S. and Canadian agencies in generating assessment-based (in part) policies and on the views of U.S. and Canadian industry on such government roles. Session II (Applications of Mineral Deposit Models to Regional Assessments) presented U.S. and Canadian case histories on the application of traditional analog (subjective probability) methods in resource assessment. Session III (Towards Quantitative Mineral Resource Assessment) considered some case histories on the application of machine-based quantitative techniques and multiparameter data-set integration in resource assessment.

The three plenary sessions were intended to set the stage for the heart of the workshop—the small group discussions organized around eight topics selected as representative of both the technical and the policy elements of resource assessments and their applications (see app. 2 for background statements on each discussion topic).

The Leesburg Workshop yielded much interesting discussion, a variety of opinion and a number of consensus conclusions concerning resource assessments and their application. These results are recorded and documented in detail in the text that follows. From an overall perspective, however, a number of the workshop's principal conclusions could form the basis for future discussions. These conclusions can be conveniently grouped into two broad categories—those relevant to the users of resource assessment products and those of concern mainly to the generators of resource assessment products.

In the user category, perhaps the most important conclusions were as follows:

1. The messages inherent in resource assessment products must be transmitted in clear and nontechnical language, unencumbered by the detailed technical qualifications and caveats so often used by technical experts.
2. The products of resource assessment must be expressed in (or be amenable to expression in) economic terms; that is, results must be expressed in quantitative terms (for example, grades, tonnages, contained metals) rather than qualitative terms.
3. Reliability or "confidence" indexes need to be attached to assessment results so that, when they are translated into economic terms, appropriate discount factors can be applied.
4. The process of improving the usefulness and application of resource assessments to public policy generation requires continuing education of both users and generators.

In the generator category, it is more difficult to distill hard and fast conclusions. Certainly, many participants recognized the inevitable trend toward the development and application of quantitative techniques. There was some skepticism, however, that such techniques would be rooted in strict mathematical, statistical, or machine-based "mimic" (logic model) approaches, such as AI and expert systems. Rather it seems probable that better quantitative approaches will be based on the evolution and refinement of comprehensive grade-tonnage models, the development of reliable probability-of-occurrence models, and the construction and testing of detailed "attribute" hierarchies for deposit-model applications. To the criticism that analog techniques are the somewhat one-dimensional basis for resource assessments, Churchill's famous dictum that "it is the worst possible system except for all others" may be applicable. Resource asessment is not yet an exact science.

On the basis of a few written submissions from participants following the workshop and many oral communications received by the organizers during and after the workshop, we have distilled these comments and recorded them in the following brief notes.

PREACHING TO THE CONVERTED

"Preaching to the converted" is undoubtedly an endemic risk whenever groups of specialists assemble to discuss topics related to their particular specialties or expertise. Many of the workshop's technical participants commented that they learned little that was new to them. On the other hand, nonspecialists (technical) and participants with policy and economic orientations tended to view many of the technical aspects of the workshop as excercises in intellectual incestuousness—members of the "club" talking to other members in a language understood only by themselves. Similarly, some technical specialists tended to find the discussions dealing with policy or economics "boring" and at times arcane. In the end, the problem is not so much organizational as it is human, since almost any endeavor will always involve two or more "cultures" representing opposing viewpoints. It could be argued that this situation resulted from mixing policy-oriented topics (Session I) and technical topics (Session II and III) and participants of both persuasions in the same venue. Conversely, it could be argued, perhaps with more conviction, that it is exactly this "two-culture syndrome" that such mixed-participant workshops attempt to tackle.

RELEVANCE

There was comment from both technical and policy and economic quarters (and much discussion focused on the issue) that resource assessment as currently practiced faces a severe "relevance" crisis. As a result, one of the important consensus conclusions of the workshop is that there is a need for quantitative estimates of undiscovered resources and that these estimates are a necessary link between geologic estimates and economic estimates. This conclusion, in turn, is linked to a second major conclusion—that there is a need for reliable probability-of-occurrence models.

Behind the perceived relevance crisis is the fact that, although resource assessments focus on resources that may not be discovered, if they even exist, for many years, the assessment process uses the models and yardsticks of current resource criteria in predicting the occurrence of such future resources. As a result of changing economic, political, technological, and industrial factors, such "future" resources may have values, characteristics, and geologic habitats that differ from the current resource yardsticks on which the assessment process is based. The "moving target" argument is familiar, and one approach that is commonly suggested is a much stronger emphasis on the economic overlay aspect of traditional analog-based geologic assessments. This criticism of many current assessment approaches is undoubtedly serious and valid. To be fair, however, this need for economic analysis has not been ignored by the many geologists who have struggled with the difficult business of attempting to predict the geologic existence of undiscovered resources. Frequently, assessment geologists have called on economists to shed some light on their labors, but the economists have not always been quick to respond, and, not uncommonly, their responses have not always been comprehensible to the geologists. Two cultures, again, speaking with collective voices, in need of simultaneous translation.

COMPREHENSIBILITY

Linked by some commentators to the question of relevance is the question of comprehensibility; in a practical sense, the two elements are indistinguishable. Given the broad spectrum of people affected by the resource assessment issue, the answer seems to be continuing dialogue. In this sense, events such as the Leesburg Workshop can be considered part of the eventual solution. If a solution, finding, or conclusion is to be useful and relevant to its applicators, it must be understandable to them also. A common criticism of resource assessment projects is that their results are cast in such technical terminology that the nontechnical user (for example, a policy analyst) can become lost in fine-tuned scientific and mathematical-statistical discourse. This criticism is probably less justified now than it was a few years ago, since geologists who produce resource assessments have become attuned to the formats and emphases needed by their clients. At the same time, many clients have learned to understand, if not to fully appreciate, the difficulties and uncertainties that geologists face in attempting to define the undefinable and predict the unpredictable, particularly in frontier areas where hard data are commonly lacking.

ORGANIZATIONAL LESSONS

A number of points made by workshop participants concerning organization and format may be useful in planning future sessions of this type. Written comments submitted after the workshop indicated a nearly universal feeling that participants benefited more from the group discussions than they did from the formal background-paper sessions. As a further indication of the different perceptions among participants, technical people generally felt that the policy sessions (Session I) could have been eliminated or compressed without much loss, whereas participants oriented toward policy or economics felt that the technical presentations (Sessions II and III) could have been shortened or dropped. In retrospect, a more appropriate balance might have been struck by compressing the formal sessions into a day and a half and leaving more time for group discussion.

Most participants seemed to feel that the "Dahlem" format, wherein a chairman and a reporter produced a written report on each group discussion for presentation and further discussion at a plenary session, worked well. This process could be improved by allowing more time for discussion of these workshop reports. It was also suggested that workshops be structured so that participants could be involved in several discussion groups, a laudable but organizationally difficult goal, given a relatively large group and a relatively short time frame.

Representation by industry, particularly the U.S. mining industry, was less than expected, perhaps in part because of an unfortunate but unavoidable conflict between the dates of the Leesburg Workshop and the American Mining Congress Annual Meeting. The depth of the workshop discussions indicates that a greater participation by mining industry representatives would have added needed insights to many of the issues under consideration. It is important that industry's experience and expertise in areas related to resource assessment (such as target-area selection) be used and, conversely, that industry (particularly senior personnel) be aware of and understand the operation and implications of the resource assessment work carried out by government agencies.

EXHIBITS

It was suggested that the information-exchange aspects of the workshop would have been improved by a poster room or an area where hard-copy examples of resource assessment products (such as maps and reports) could have been displayed.

CONCLUSIONS

On balance, it can be concluded that the Leesburg Workshop served its primary purpose of bringing together, for a few days, people interested in the same topics to exchange information and observations on the processes, mechanisms, and technologies of resource assessment and to attempt to define some trends and requirements of the future. The workshop demonstrated that there is a genuine community of interest in resource assessment, on the part of both generators and users, that there will be a continuing need for improved and more reliable estimates, and that there are many things yet to be learned and many problems yet to be solved.

Finally, a note on the organization of this report. The material presented at the workshop as plenary papers and the proceedings of the discussion groups have been combined and are presented in the context of the two categories set forth earlier. "The User's Perspective" deals with resource assessment from the viewpoint of those who use assessment results. "The Technical Persepective" presents, for the most part, the papers and discussion records most relevant to the viewpoint of the scientists and technical experts involved in conducting resource assessments. Some presentations have been included in this volume as abstracts, either because the full papers have been accepted for publication elsewhere or because the research is not advanced enough to warrant a complete documentation. "Conclusions and Critiques" attempts to bridge the two categories and to draw out some of the main conclusions and critiques reached.

This introduction would not be complete without an expression of thanks by the organizers to all who participated. In particular, we express our gratitude to Simon Cargill (USGS) and Steven Green (GSC), who were responsible for the local arrangements and who attended ably and cheerfully to the wants and needs of the participants.

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USGS Workshop Convenor
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THE USER'S PERSPECTIVE

NATIONAL GEOSCIENCE PROGRAMS: A BASE FOR RESOURCE ASSESSMENTS OF CANADIAN LANDS

By W. W. Hutchison
Energy, Mines and Resources Canada

INTRODUCTION

Mineral resource assessments in Canada are not new. We can trace their antecedents back to the time of Sir William Logan, the first Director of the Geological Survey of Canada, who, in 1842, was voted the princely sum of 1,500 pounds sterling and instructed by the Parliament of "the Province of Canada" to "cause a Geological Survey of the Province to be made, for the purposes of ascertaining the Mineral Resources thereof." Although terminology and methods have changed greatly since Logan's time, the basic objective remains the same: to exercise wise stewardship, a government needs to know what it has responsibility for, whether it be mineral resources, fuel resources, sites for permanent disposal of nuclear wastes, or water resources to sustain agriculture. Determining the answers to questions about resource potential obviously has many aspects, but the process depends fundamentally on scientific information about those resources and an understanding of their environments and their mechanisms of formation. I would like to focus on Canadian experience in some of these matters.

BACKGROUND: CANADA'S MINERAL ECONOMY

Since we are talking about mineral resources, it may be useful to begin with a reminder of the extremely important role that minerals play in Canada's economy (fig. 1). The value of Canadian mineral production (including fuels) is about $43 billion (Canadian). To put this figure in perspective, minerals and fuels account for nearly 10 percent of our gross national product and over 20 percent of Canada's export earnings. There are about 300 underground and open-pit mines in Canada and about 175 communities that are primarily dependent on mining for their existence. About 50 percent of all domestic rail traffic is minerals or mineral products. Our mineral production and exports are diversified; there are some 60 commodities on the list, although a dozen leading commodities account for about 85 percent of production.

The Canadian mineral industry, like those of many western nations, has experienced tough times over the past few years. We recognize that major structural changes and shifts in demand and prices will continue to challenge the industry. It is our role to ensure that our geoscience programs will contribute to the continuing success of the industry in the future, especially in measures that can stimulate the discovery of new resources.

RESOURCE ASSESSMENT: AN ESSENTIAL NEED

The reasons why a government is obligated to assess and evaluate its resources are clear and compelling; a government's failure to make such assessments would be analogous to a corporation's being involved in an economic venture without knowing what

Canada

Landmass	9.97×10^6 km^2
Offshore	6.5×10^6 km^2
Total territory	16.47×10^5 km^2
Population	25.2×10^6
Population Density	2.5/km^2 (U.K. - 125.5/km^2; FRG - 248/km^2 Japan - 313.1/km^2)
GNP	429.9 ($\$ \times 10^9$) (1984)

Value of Mineral Production

	1983	1984
	($\$ \times 10^9$)	
Metals	7.40	8.51
Non-Metals	1.90	2.27
Fuels	27.15	30.00
Structural Materials	1.83	1.91
Other Minerals	.24	.38
Totals	38.52	43.07

Minerals in the Economy

% of GNP	10
% of total exports	20
Principal Markets	U.S.A., EEC, Japan

FIGURE 1.—Fundamental demographic and mineral production statistics for Canada (1984).

its assets and prospects were. I should stress that, in Canada, as many of you may be aware, the Provinces have jurisdiction over all their mineral resources and thus over much resource-based economic development. The Federal Government's primary resource responsibilities are in the northern territories (Yukon and Northwest Territories) and in the offshore territory. In addition, however, the Federal Government exerts national jurisdiction over resources through taxation and grant measures, import and export controls, certain investment instruments, and resource information. Let me now discuss briefly some of the reasons for resource assessment: the need to know, export

	1984 VALUE ($\times 10^9$ \$)	RANK (DOMESTIC)
FUELS		
CRUDE PETROLEUM	17.9	1
NATURAL GAS	7.6	2
COAL	1.8	3
METALS		
IRON ORE	1.5	4
ZINC	1.4	5
COPPER	1.4	6
GOLD	1.2	7
NICKEL	1.2	8
URANIUM	.9	9
SILVER	.4	15
NON METALS AND STRUCTURAL MATERIALS		
POTASH	.8	10
CEMENT	.7	11
SULFUR (ELEMENTAL)	.6	12

37.4 (≃85% OF TOTAL VALUE)

FIGURE 2.—Production values of Canada's leading mineral commodities.

controls, trade negotiations, exploration and investment incentives, land use policy, and jurisdictional disputes.

Need to Know: Basic Resource Information

In order to make optimum use of what you have—whether it be trees, dollars, books, or resources—you must know what you have. The difficulty, of course, is that mineral and fuel resources are not items that can be easily counted in a normal inventory process. We are dealing in large part with intangibles in the form of undiscovered resources. As such, the "inventory" process is difficult and commonly subjective and yields no final, absolute answers.

Export Controls

Is there enough of a resource or commodity to meet domestic requirements before a surplus is declared for export? The answer to this question is obviously dictated by the policy needs that may be linked to a strategic commodity. Canadian federal petroleum and uranium policies are determined by this tenet.

Trade Negotiations

Bilateral and multilateral (for example, the General Agreement on Tariffs and Trade) trade arrangements require knowledge of the present and future availability of any domestic resource commodity that may require negotiations to yield fair tariff treatment.

Exploration Incentives

Resource assessments based on sound geoscience information may identify potential new or overlooked environments for exploration. We have seen this situation recently in Canada in the cases of uranium and, to a lesser degree, of platinum-group metals.

Investment Incentives

The results of resource assesment projects may provide incentives for foreign corporations to undertake mineral exploration and development projects. Also, financial institutions may rely on government assessments—considered to be "neutral" or unbiased--for guidance in making decisions on loans in resource development projects.

Land Use Policy

Policies and mechanisms for determining the most effective use of lands require mineral and fuel resource assessments for assigning "future values" for lands. In Canada, as perhaps in the United States, this need has been one of the major influences in the development of formal assessment programs (wilderness areas, national parks, and so on). Additional issues, such as settlement of native peoples' land claims, are referred to by Neil Faulkner and others in this volume.

Jurisdictional Disputes

The eventual resolution of territorial or boundary disputes may depend heavily on assessments of contained or anticipated resources.

EVOLUTION OF RESOURCE ASSESSMENT IN CANADA

As I noted earlier, the concept of resource assessment is not new in Canada. Nevertheless, the formal discipline of resource assessment is a relatively recent development. The first formal assessment projects were carried out in connection with global surveys of iron ore (late 1950's) and uranium (1960's) sponsored by UN agencies. Since then, a number of projects and programs have been undertaken (table 1).

Here I would like to emphasize two points. The first is that many of the earlier projects were categorized as "quantitative" assessments; that is, they attempted to express results in numerical terms (numbers of deposits expected, grades and tonnages, and so on). Perhaps, for us, the peak of this trend was reached with what is referred to informally as "Operation September," a project carried out in 1972 by the Department of Energy, Mines and Resources (EMR) to derive quantitative national estimates of six major commodities (iron ore, copper, lead, zinc, nickel, and molybdenum). Those estimates were updated and published in 1976 (see example, fig. 3). One lesson that we learned from those early attempts was that the existing information base and methodologies were inadequate to support rigorous analyses. Following this period, most assessment projects were conducted in qualitative terms, and there was a movement away from expressing results in numbers.

The other point of interest is that, among the assessment projects carried out over this period of approximately 20 years, two groups later evolved into formal programs that are still going on—the uranium resource assessments and the northern mineral assessments. A third important category was the national oil and gas assessment program. I would like to use these three categories to illustrate briefly the historical evolution of formal assessment programs in Canada.

RESOURCE ASSESSMENT PROGRAMS IN CANADA

A variety of different resource assessment systems is in use around the world. Many, including various early Canadian projects, rely mainly on statistical extrapolation from existing data without the input of new information concerning geologic features and interpretations, data on the characteristics of mineral and fuel deposits, and other "prospectivity" factors (fig. 4). In our current assessments, we are attempting to build sequentially on the basis of the following steps:

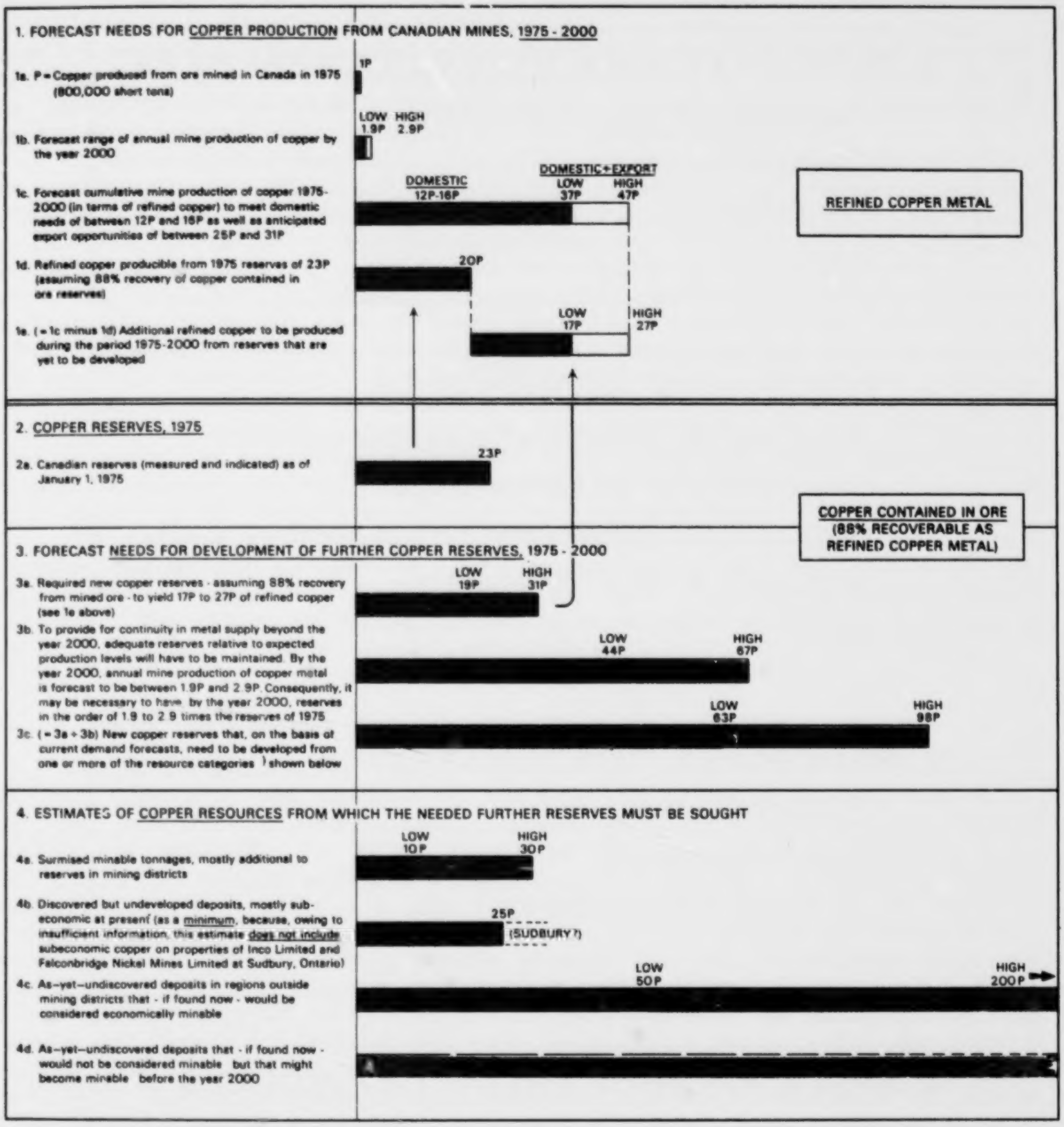
1. Acquiring the best available relevant new data.
2. Using skilled expertise to create a "portrait" that emphasizes the character of the fuel or mineral deposits being sought and its local geologic environment.
3. Unraveling the processes of formation and historical evolution of the resource deposit to derive a deposit model.
4. Applying the deposit model in a predictive manner to target environments for new deposits or possible extensions to known deposits.

Oil and Gas Resource Estimates

The world oil crisis of 1973-74 and subsequent OPEC price setting affected Canada as they did most nations. Government responses led to a range of new mechanisms, including incentives to spur frontier oil and gas exploration.

TABLE 1.—Some Canadian resource assessment studies

IDENT	YEAR	AUTHOR(S)	AREA	COMMODITIES REPORTED	METHOD	FORM OF RESULTS
1	1958	LANG (GSC)	CANADA	URANIUM	GEOLOGICAL	QUALITATIVE
2	1966	ROSCOE (GSC)	CANADA	URANIUM, THORIUM	GEOLOGICAL	QUALITATIVE
3	1967	GROSS (GSC)	CANADA	IRON	GEOLOGICAL	QUALITATIVE
4	1969	KELLY & SHERIFF	BRITISH COLUMBIA	VARIOUS	GEOSTATISTICAL	QUANTITATIVE
5	1970	BARRY & FREYMAN	NORTHERN B.C. AND YUKON	VARIOUS	SUBJECTIVE PROBABILITY (DELPHI)	QUANTITATIVE
6	1970	DEGEOFFREY & WU	CANADIAN SHIELD	VARIOUS (DOLLAR VALUES)	PROBABILISTIC	QUANTITATIVE
7	1971	DEGEOFFREY & WIGNALL	GRENVILLE PROVINCE (PART OF)	VARIOUS (DOLLAR VALUES)	PROBABILISTIC	QUANTITATIVE
8	1972	AGTERBERG ET AL (GSC)	ABITIBI DIST.	COPPER, ZINC	GEOSTATISTICAL (MULTIVARIATE ANAL.)	QUANTITATIVE
9	1972	AZIS ET. AL.	N. MANITOBA	VARIOUS	SUBJECTIVE PROBABILITY (DELPHI)	QUANTITATIVE
10	1972	E.M.R.	CANADA ("OPERATION SEPTEMBER")	Cu, Pb, Zn, Mo, Ni, U, Fe	GEOLOGICAL	QUANTITATIVE
11	1973	DERRY	ARCTIC & SUB-ARCTIC	Cu,Pb,Zn,Au,Fe	GEOLOGICAL	QUANTITATIVE
12	1973-76	**McCARTNEY AND MATHESON**	BRITISH COLUMBIA	VARIOUS	GEOL. PROBABILITY	QUALITATIVE
13	1975	(GSC)	APPALACHIANS	VARIOUS	GEOSTATISTICAL	QUANTITATIVE
14	1976	**RACHMALLA AND BELL**	ONTARIO	ZINC	SUBJECTIVE PROBABILITY	QUANTITATIVE
15	1977	E.M.R.	CANADA	Cu,Pb,Zn,Mo,Ni,Fe	GEOLOGICAL	QUANTITATIVE
16	1975-80	E.M.R.	CANADA	URANIUM	GEOLOGICAL/ GEOSTATISTICAL	QUANTITATIVE
17	1980	MAN. DIV. OF MINERAL RESOURCES /E.M.R.	MANITOBA	Cu, Zn, Ni	GEOLOGICAL	QUALITATIVE
18	1978	GSC (OF 492)	WESTERN ARCTIC	VARIOUS	GEOLOGICAL	QUALITATIVE
19	1980	GSC (OF 691)	N. YUKON & NWT (PARTS OF)	VARIOUS	GEOLOGICAL	QUALITATIVE
20	1978	AGTERBERG & DIVI (GSC)	APPALACHIANS	Cu, Pb, Zn	GEOSTATISTICAL	QUANTITATIVE
21	1977	GSC (OF 716)	N. YUKON, NWT (PARTS OF) & ARCTIC ISLANDS	VARIOUS	GEOLOGICAL	QUALITATIVE
22	1981	FINDLAY ET. AL. (GSC)	ARCTIC ISLANDS	VARIOUS	GEOLOGICAL	QUALITATIVE
23	1981	AGTERBERG ET. AL. GSC (OF 718)	S. DISTRICT OF KEEWATIN, NWT	VARIOUS	GEOSTATISTICAL	QUANTITATIVE
24	**1981a**	GSC (OF 760)	N. YUKON	VARIOUS	GEOLOGICAL	QUALITATIVE
25	**1981b**	GSC (OF 786)	N. ELLESMERE IS	VARIOUS	GEOLOGICAL	QUALITATIVE
26	1982	SINCLAIR ET. AL. (GSC IN PREP)	YUKON	VARIOUS	GEOLOGICAL	QUALITATIVE



1. FORECAST NEEDS FOR COPPER PRODUCTION FROM CANADIAN MINES, 1975 - 2000

1a. P = Copper produced from ore mined in Canada in 1975 (800,000 short tons)

1b. Forecast range of annual mine production of copper by the year 2000

1c. Forecast cumulative mine production of copper 1975-2000 (in terms of refined copper) to meet domestic needs of between 12P and 16P as well as anticipated export opportunities of between 25P and 31P

1d. Refined copper producible from 1975 reserves of 23P (assuming 88% recovery of copper contained in ore reserves)

1e. (= 1c minus 1d) Additional refined copper to be produced during the period 1975-2000 from reserves that are yet to be developed

2. COPPER RESERVES, 1975

2a. Canadian reserves (measured and indicated) as of January 1, 1975

3. FORECAST NEEDS FOR DEVELOPMENT OF FURTHER COPPER RESERVES, 1975 - 2000

3a. Required new copper reserves - assuming 88% recovery from mined ore - to yield 17P to 27P of refined copper (see 1e above)

3b. To provide for continuity in metal supply beyond the year 2000, adequate reserves relative to expected production levels will have to be maintained. By the year 2000, annual mine production of copper metal is forecast to be between 1.9P and 2.9P. Consequently, it may be necessary to have by the year 2000, reserves in the order of 1.9 to 2.9 times the reserves of 1975

3c. (= 3a + 3b) New copper reserves that, on the basis of current demand forecasts, need to be developed from one or more of the resource categories shown below

4. ESTIMATES OF COPPER RESOURCES FROM WHICH THE NEEDED FURTHER RESERVES MUST BE SOUGHT

4a. Surmised minable tonnages, mostly additional to reserves in mining districts

4b. Discovered but undeveloped deposits, mostly subeconomic at present (as a minimum, because, owing to insufficient information, this estimate does not include subeconomic copper on properties of Inco Limited and Falconbridge Nickel Mines Limited at Sudbury, Ontario)

4c. As–yet–undiscovered deposits in regions outside mining districts that - if found now - would be considered economically minable

4d. As–yet–undiscovered deposits that - if found now - would not be considered minable but that might become minable before the year 2000

FIGURE 3.--Summary of copper production, reserves, and resources in Canada, 1975-2000.

A critical aspect of coping with new post-OPEC energy realities was the need to quickly assemble and analyze a vast amount of geoscience data to provide a base for accurate inventories and estimates of Canada's known and potential (undiscovered) oil and gas resources. New and sophisticated assessment methodologies had to be developed.

In 1977, new consolidated estimates of Canada's energy reserves and resources formed much of the scientific and technical basis for parts of the nation's evolving energy policies. During the period leading up to the 1977 estimates, the Government had put in place a mechanism for the systematic generation of oil and gas estimates. Three agencies are involved in this process. Reserve data for the western Canada sedimentary

1. BEST AVAILABLE RELEVANT NEW DATA
    - Regional & local geology
    - Tectonic history
    - Geophysics, geochemistry
    - etc.

2. "PORTRAITS" OF DEPOSITS
    - Physical & chemical characteristics
    - Depositional environments
    - Signatures (geochemical, geophysical)
    - Isotopes & geochronology
    - etc.

3. PROCESSES OF FORMATION
    - PT conditions
    - Fluid regimes
    - Alteration processes
    - etc.

4. APPLICATION OF PREDICTIVE MODELS
    - Qualitative & quantitative assessments

5. HINDSIGHT STUDIES

WHERE DID WE GO WRONG ?

FIGURE 4.—Key elements in a modern sequential approach to resource assessment.

basin are assembled by the National Energy Board; estimates of reserves and discovered resources for frontier areas (northern territories and offshore regions) are provided by the Canada Oil and Gas Lands Administration; and estimates of potential resources (all regions) are generated by the Geological Survey of Canada (GSC).

To discharge its responsibility to provide continuing estimates of potential oil and gas resources, the GSC established the Petroleum Resource Appraisal Seretariat as a unit within its Institute of Sedimentary and Petroleum Geology in Calgary. The secretariat has developed and refined an appraisal methodology that integrates pool and exploration play estimates in probability terms to yield estimates of oil and gas quantities at basin levels, expressed in three probability categories (high confidence, average expectation, and speculative estimates). Over the years, this methodology has evolved from simplistic volumetric calculations to the current probablistic method, applied at the exploration play level and incorporating "objective" data (seismic records, stratigraphic thickness, porosity, depth, maturation levels, and so on) and informed geologic opinion (regional tectonics, local structures, closure estimates, fluid regime models, thermal and subsidence histories, and so on) to derive the input variables for play estimates. Above all, the methodology rests on geologic knowledge and the characteristics of pools and plays derived through cumulative experience from producing fields.

The most recent national consolidated estimates were published in 1974. Figure 5 compares conventional oil resource estimates published in 1975 and 1983 for the six major petroleum regions of Canada. You will note that reserves and discovered resources in the western Canada sedimentary basin decreased by about 40 percent over this 8-year period, whereas increases in potential were inferred for all other regions.

Influence of Assessments

I want to emphasize that Canada's experience in assessing its domestic oil and gas resources illustrates well the role of scientific and technical analysis both as an important generator in the formulation of national policy and as a product driven by the need for new policy (fig. 6). In the latter case, the realization in the late 1960's and early 1970's that national estimates were inadequate to provide a solid footing for new energy policies accelerated the improvement and systematization of the appraisal process. These improvements, in turn, led quickly to improved resource estimates that could be absorbed into the policy generation process. One thrust of the newly generated policies was a concerted effort to move Canada toward energy self-sufficiency, in part through policies designed to shift exploration emphasis from the established western Canada basin toward the frontier areas—the Arctic islands and the east coast offshore regions. This shift, in turn, drove the system to acquire new geoscientific data, which provided the information needed for new estimates of production potential in the frontier areas. Again, I emphasize the sequential flow in the system that I mentioned earlier—from regional and local geologic knowledge through the assessment process to the translation of results into a simplified format for economic and policy analysis and finally to decisionmaking.

Uranium Resource Estimates

Canada began compiling national estimates of uranium reserves and resources in the 1950's and 1960's, initially largely for global surveys conducted by the UN Conferences on the Peaceful Uses of Atomic Energy and later (post-1964) for the International Atomic Energy Agency. In 1974, the Canadian Government established the Uranium Resource Appraisal Group (URAG), composed of units within the Canada Centre for Mineral and Energy Technology, the GSC, and the Uranium and Nuclear Energy

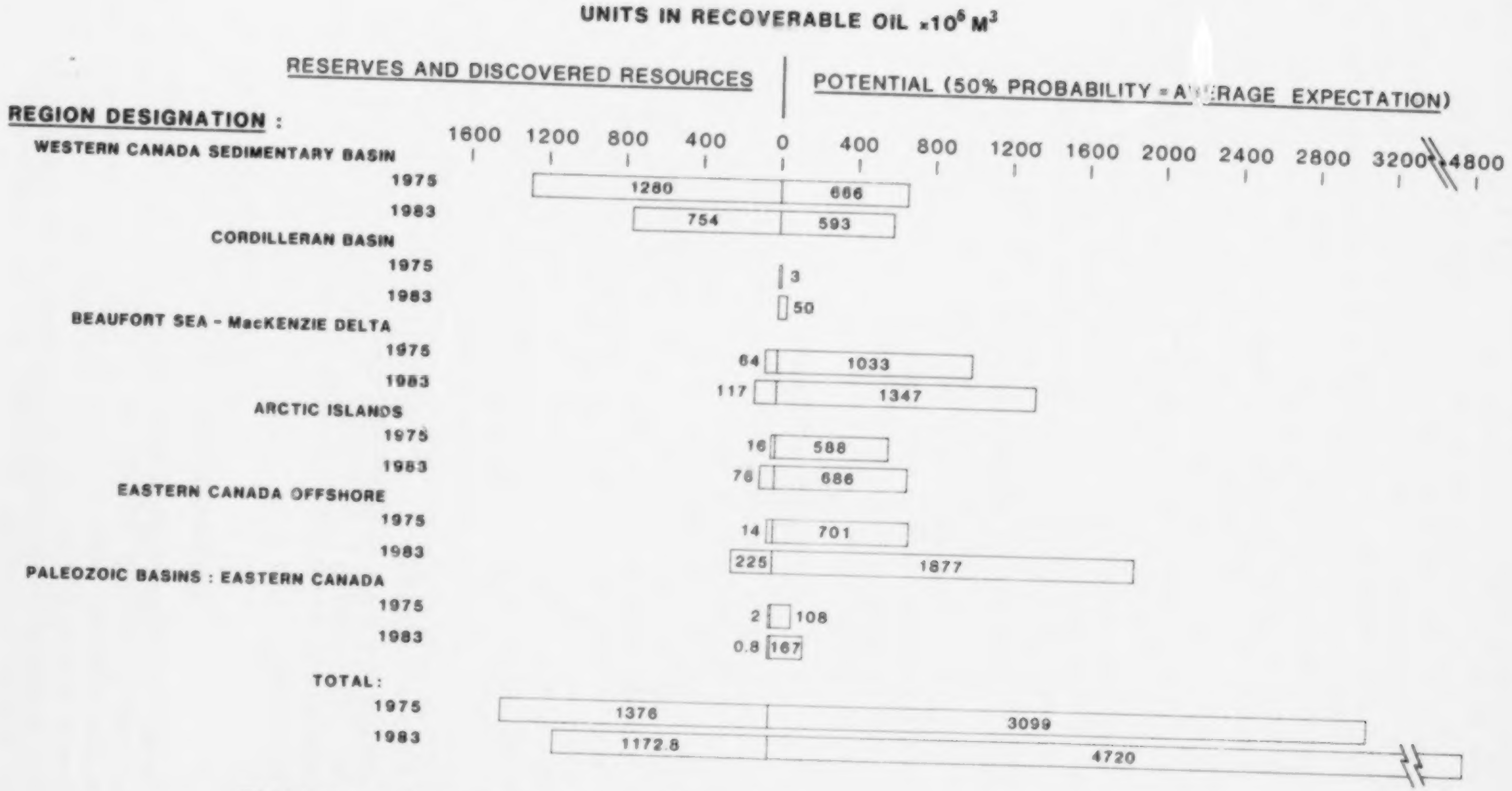


FIGURE 5.—Comparison of conventional oil assessments made in 1975 and 1983.

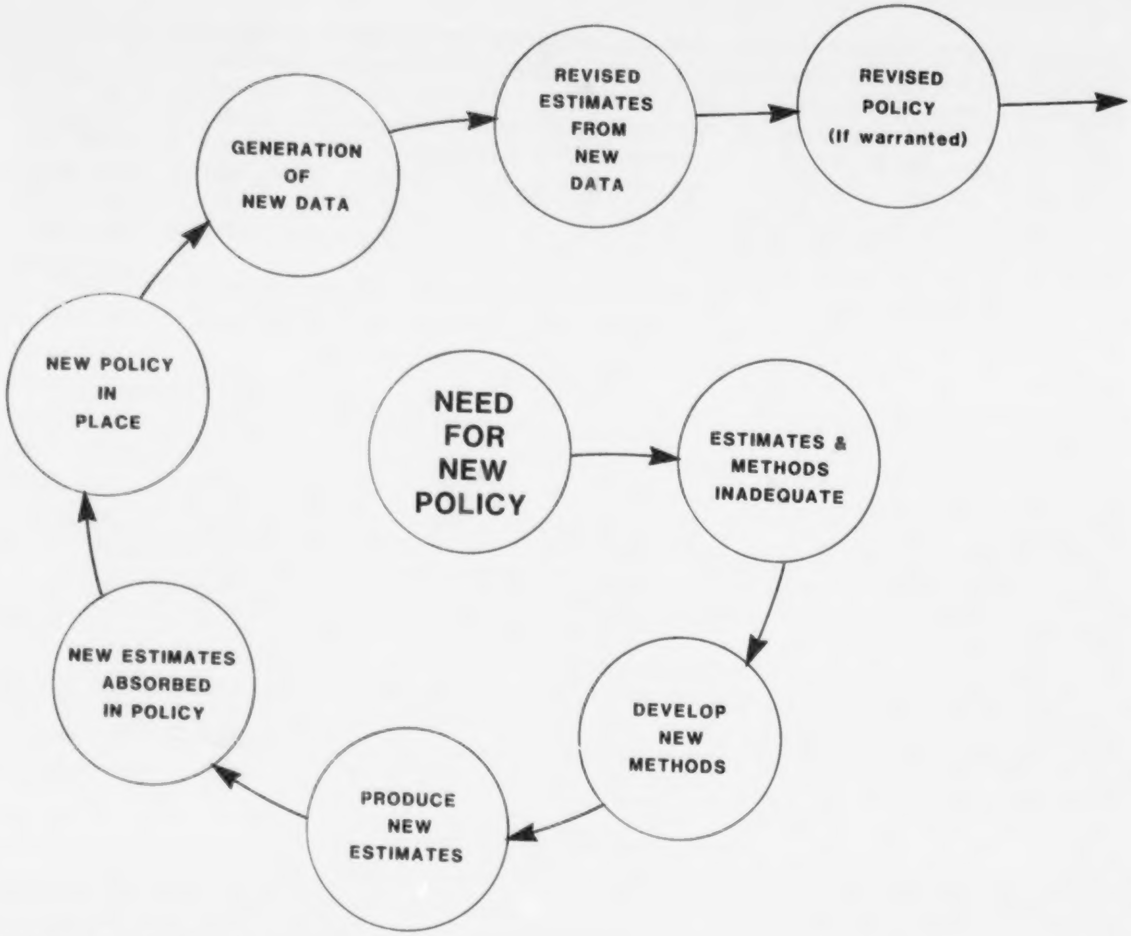

NEED FOR NEW POLICY
ESTIMATES & METHODS INADEQUATE
DEVELOP NEW METHODS
PRODUCE NEW ESTIMATES
NEW ESTIMATES ABSORBED IN POLICY
NEW POLICY IN PLACE
GENERATION OF NEW DATA
REVISED ESTIMATES FROM NEW DATA
REVISED POLICY (If warranted)

FIGURE 6.--Role of scientific and technical analysis in the formulation of new national mineral policy.

Branch of EMR. Between 1975 and 1981, EMR published URAG assessments of Canada's uranium supply and requirements annually; since 1982, publication has been biennial.

The URAG process parallels to some degree the mechanisms used for oil and gas assessments, although the assessment methodologies are different (fig. 7). Reasonably assured resources (measured and indicated) are calculated by the Canada Centre for Mineral and Energy Technology on the basis of information supplied by uranium producers and supplemented by evaluation visits by the URAG Subcommittee on Reasonably Assured Resources. Estimates of additional resources (inferred and prognosticated) associated with known deposits and districts and speculative resources in geologically favorable regions outside producing camps are provided by the GSC. The third component, the URAG subcommittee on Economic Coordination, is responsible for balancing known resources against domestic requirements and export commitments and for determining how much uranium is to be reserved for domestic reactor requirements.

Influence of Assessments

Canada's uranium assessment process has been linked to policy formulation in two main ways. Uranium export contracts must be approved by the Federal Government

(Atomic Energy Control Board), and the export permit process is based on providing a "protected" supply for domestic reactors before a surplus (to domestic needs) is made available for exploration. Canadian policy requires (1) that domestic reserves be sufficient to fuel each reactor currently onstream or planned for production within the next 10 years (at an average 80 percent annual generated capacity) for 30 years from 1983 or from the startup date of the reactor, whichever is later; and (2) that export permits be limited to a 15-year forward period to provide additional protection for the 30-year reserve. The continuing generation of uranium resource estimates thus plays a critical role in the management of Canada's uranium policy.

Recognizing the need for improved geoscience information as a component of uranium policy, the GSC, in cooperation with provincial government agencies, began a

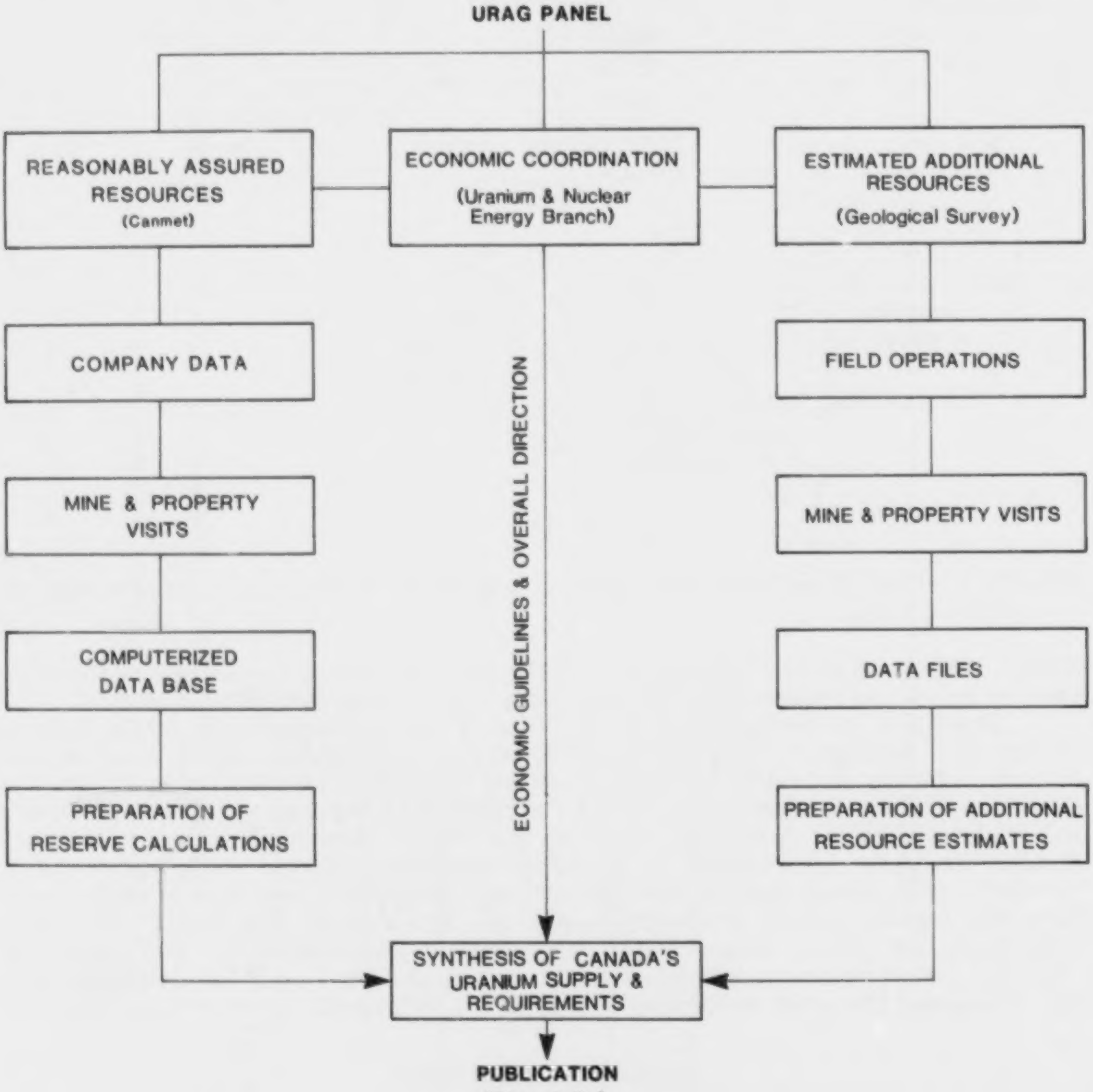

URAG PANEL
REASONABLY ASSURED RESOURCES (Canmet)
ECONOMIC COORDINATION (Uranium & Nuclear Energy Branch)
ESTIMATED ADDITIONAL RESOURCES (Geological Survey)
COMPANY DATA
MINE & PROPERTY VISITS
COMPUTERIZED DATA BASE
PREPARATION OF RESERVE CALCULATIONS
ECONOMIC GUIDELINES & OVERALL DIRECTION
FIELD OPERATIONS
MINE & PROPERTY VISITS
DATA FILES
PREPARATION OF ADDITIONAL RESOURCE ESTIMATES
SYNTHESIS OF CANADA'S URANIUM SUPPLY & REQUIREMENTS
PUBLICATION (Biennially)

FIGURE 7.—Assessment methodology in the uranium resource appraisal process.

10-year, $30 million Uranium Reconnaissance Program (URP) in 1975. URP consisted mainly of airborne radiometric and stream- and lake-sediment geochemical surveys. When the program was terminated in 1979 as an economy measure, $17 million had been expended in providing reconnaissance uranium data for about 25 percent of the country. The geoscience data released as a result of this program stimulated widespread company exploration activities in various regions of Canada and provided much-needed new information for the URAG assessment process. Again, we see the same linkage between geoscience data, the appraisal process, and policy needs, as the oil and gas example illustrated.

Northern Mineral Resource Assessments

Beginning in the late 1970's, the GSC began conducting mineral resource assessments of various regions in Canada's northern territories. Initially, these assessments were required for two main purposes: (1) to aid in the evaluation of northern lands for negotiations between the Federal Government and various native peoples organizations (land claim negotiations) and (2) to aid in the evaluation of proposed northern national parks and lands to be set aside for other conservation purposes.

Initial assessments were performed on an ad hoc, "on-demand" basis, but, because of the increasing work load placed on the GSC as a result of the continuing demand for these services, the process was formalized in 1980 by the establishement of an interdepartmental committee consisting of representatives from EMR, the Department of the Environment, and the Department of Indian Affairs and Northern Development. This Working Committee for Northern Mineral and Energy Resource Assessment (MERA) coordinates the requirements for producing northern mineral assessments (fig. 8).

Influence of Assessments

The Federal Government now requires, for example, that lands proposed to be set aside for northern national parks (6 national parks are now established in the northern territories, and an additional 8 to 10 are planned) be subject to the MERA evaluation process. This process can have an impact on national parks policy by ensuring that mineral and fuel potential will be considered in the selection of park lands.

I will not elaborate too much on this example, since Neil Faulkner and others address various aspects of this program elsewhere in this volume. In terms of "influence," you will hear how one particular assessment project (Bathurst Inlet) resulted in a policy decision to defer the establishment of a park in an area considered to have significant mineral potential.

RESOURCE ASSESSMENTS AND THE FUTURE

We can draw a number of conclusions from our experience with resource assessment in Canada. The first is that, undoubtedly, we will be called upon to do more, and we will be expected to do it better. Perhaps the most important lesson that we have learned is that it is unwise to divorce the processes of resource assessment from the processes of conducting solid, quality scientific research on mineral and fuel deposits and their geologic environments. We know, for example, that, if we want to produce estimates of the potential for mineral deposits in the ophiolite terranes of eastern Canada, we must first provide ourselves with a good understanding of the ophiolite packages and their petrochemical and tectonic histories and then integrate with that understanding the modern mineral deposit models applicable to those particular terranes.

In our efforts to predict the residual exploration potential of existing Precambrian Shield volcanogenic massive sulfide camps (for example, Noranda and Timmins), we will rely on deposit models generated by the cumulative geologic experience and expertise in these camps. We will also incorporate into this process the exciting new information coming from current investigations of modern massive sulfide analogs being formed on the sea floor along the Juan de Fuca Ridge off the western coast. In addition, the sea-floor sulfide deposits themselves provide a major new assessment challenge. Apart from the light that they may throw on the formation mechanisms of their ancient land analogs, we must assess their economic potential in its own right. Although present indications are that the ridge axis sea-floor deposits are an order of magnitude smaller than land

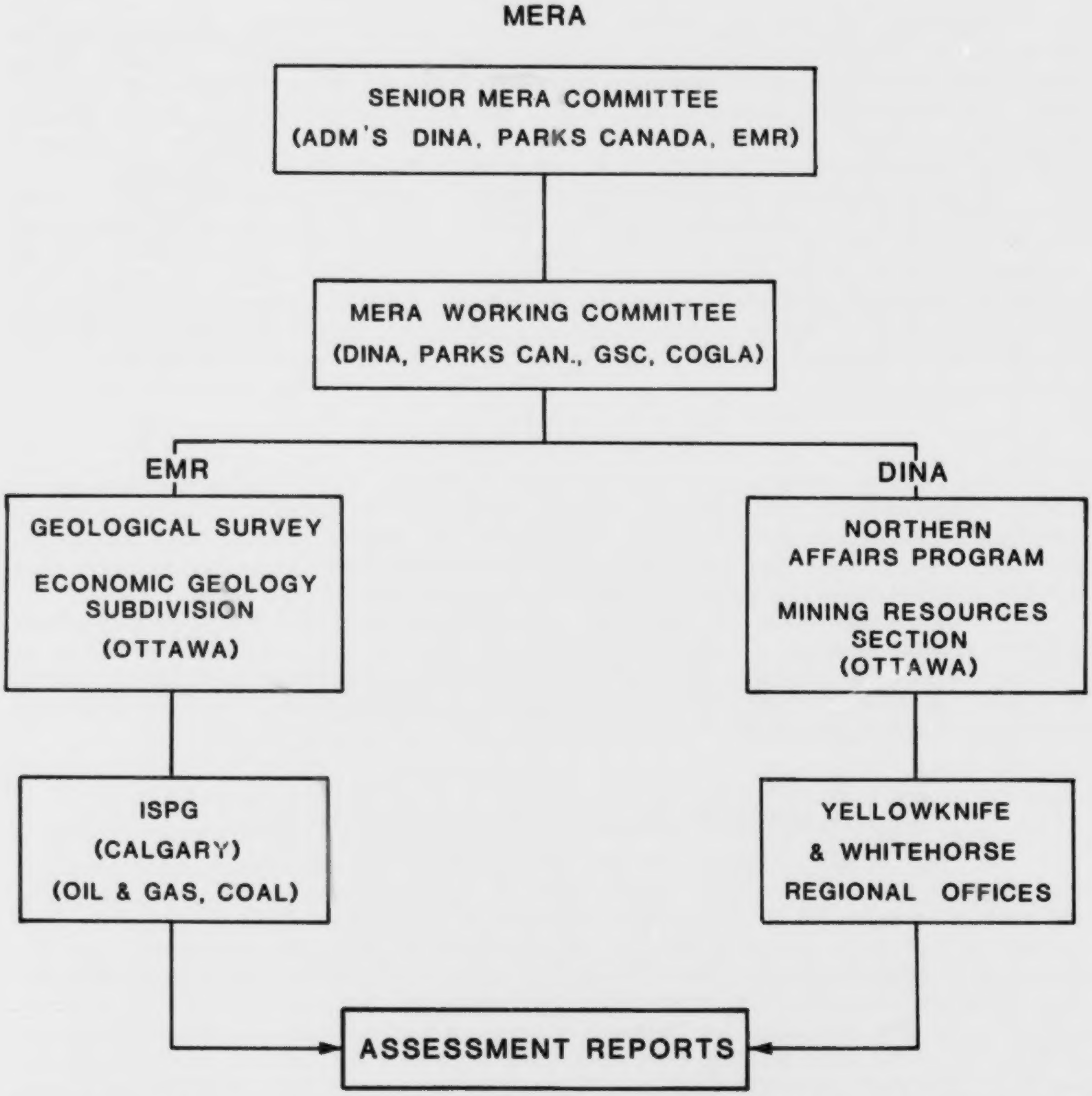

MERA
SENIOR MERA COMMITTEE
(ADM'S DINA, PARKS CANADA, EMR)
MERA WORKING COMMITTEE
(DINA, PARKS CAN., GSC, COGLA)
EMR
GEOLOGICAL SURVEY
ECONOMIC GEOLOGY SUBDIVISION
(OTTAWA)
DINA
NORTHERN AFFAIRS PROGRAM
MINING RESOURCES SECTION
(OTTAWA)
ISPG
(CALGARY)
(OIL & GAS, COAL)
YELLOWKNIFE
& WHITEHORSE
REGIONAL OFFICES
ASSESSMENT REPORTS

FIGURE 8.—Internal structure and role of MERA in producing northern mineral resource assessments.

deposits, some evidence suggests that off-ridge and seamount environments may reveal deposits comparable in size to classic onshore massive sulfide environments.

At the GSC, we have now decided that the approach to resource assessment must be holistic. We cannot regard resource assessment as a specialized, compartmentalized activity but rather as one of the many outputs that necessarily draw from a broad spectrum of scientific research. We recognize the mineral deposit model as a key ingredient in that spectrum, and, to this end, we have been focusing a significant part of our research effort on improving our knowledge of mineral deposit models applicable to Canadian terranes. You will hear more about this topic later, so I will not dwell on it here. I would draw your attention, however, to a recent publication of the GSC (Eckstrand, 1984) that summarizes our current thoughts on some 40 Canadian mineral deposit types.

I might conclude with an illustration of the application of the deposit model to one of our resource assessment projects. I choose this example because it illustrates schematically a point that I would like to emphasize—the importance of integrating a variety of systematic geoscience data into the assessment process. The general situation is shown in figure 9, where we see two streams of information, interpretations, and concepts; one stream is on the local mineral deposit scale, and the other is on the regional metallogenic scale. These streams lead to the development of the operational deposit model. Figure 10 shows (again schematically) the matching of the geoscience data with the attributes of a particular deposit model (shale-hosted massive sulfide) considered applicable to the terrane in question, in this case a rift zone on northern Baffin Island. There is one producing mine (the Nanisivik lead-zinc mine) in the north Baffin rift zone as well as a number of other smaller occurrences. Because the mine and many of the smaller occurrences are carbonate-hosted deposits in Proterozoic dolomite, most exploration attention has been directed at the possibility of finding additional deposits of the same type. The results of the assessment project suggested, however, that there also exists exploration potential in the extensive black shale terrane that forms part of the Proterozoic package of this region. The assessment results have not, to our knowledge, resulted in new discoveries in the region, but exploration continues.

CONCLUDING REMARKS

To conclude, I would stress that we view mineral resource assessment as one of the logical evolutions of our mission, set out long ago for Sir William Logan—the continuing process of "ascertaining the mineral and fuel resources of our country." We prefer the holistic approach; that is, the cumulative total of our geoscience knowledge and experience provides the background from which we can draw scientific and technical assessments to serve a variety of "clients" or uses. Governments can use these assessments as inputs to economic and policy analysis and land use planning; if they are based on sound, state-of-the-art geologic and metallogenic thinking, industry can apply them in exploration; if they are (and are seen to be) unbiased and objective, financial institutions can use them in evaluating loan and investment instruments. Finally, if our methodologies withstand the rigorous scrutiny of our scientific peers, they can be incorporated in reports and journals on current research.

Geoscientists must be able to translate the results of our assessments into nontechnical terms that can be understood and used by policymakers' economic analysts. As a secondary consideration, we must exercise caution in the "warranties" and caveats that we may attach to our assessment products. Although we can now make fairly confident predictions if we have the sort of adequate data base that exists for petroleum resources, we all recognize that we still have a long way to go to produce comparable results for most metals.

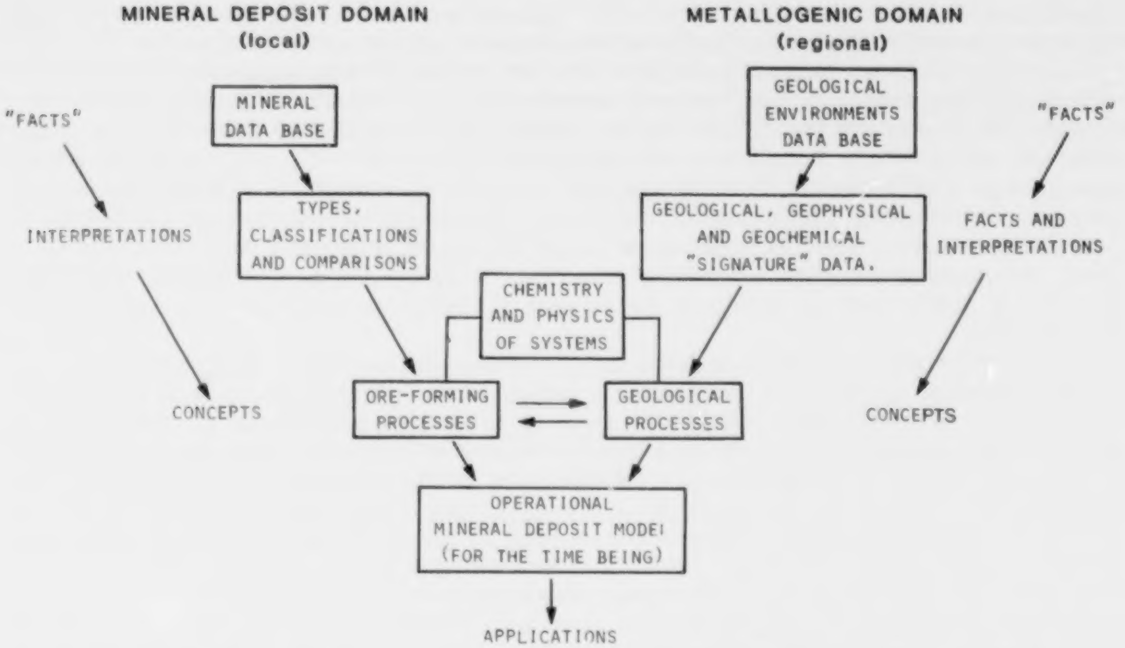

MINERAL DEPOSIT DOMAIN
(local)
METALLOGENIC DOMAIN
(regional)
"FACTS"
MINERAL DATA BASE
GEOLOGICAL ENVIRONMENTS DATA BASE
"FACTS"
INTERPRETATIONS
TYPES, CLASSIFICATIONS AND COMPARISONS
GEOLOGICAL, GEOPHYSICAL AND GEOCHEMICAL "SIGNATURE" DATA.
FACTS AND INTERPRETATIONS
CHEMISTRY AND PHYSICS OF SYSTEMS
CONCEPTS
ORE-FORMING PROCESSES
GEOLOGICAL PROCESSES
CONCEPTS
OPERATIONAL MINERAL DEPOSIT MODEL (FOR THE TIME BEING)
APPLICATIONS

FIGURE 9.--Development of operational deposit model from local deposit and regional metallogenic data.

We emphasize that our geological surveys are not statistical recordkeepers and that we do not deal with items that can be counted. We deal with complex interfaces between facts, interpretations, and concepts, and our products reflect the statistical "slipperyness" of these complexities. Consequently, I return to the point that I emphasized earlier concerning the critical sequential relation between good, relevant geoscientific information and the construction of an accurate portrait of the target as a basis for deriving process-genetic models, which in turn allow application of these models in a predictive sense. These ingredients, it seems to me, are critical in the resource assessment process and are required to satisfy all user groups.

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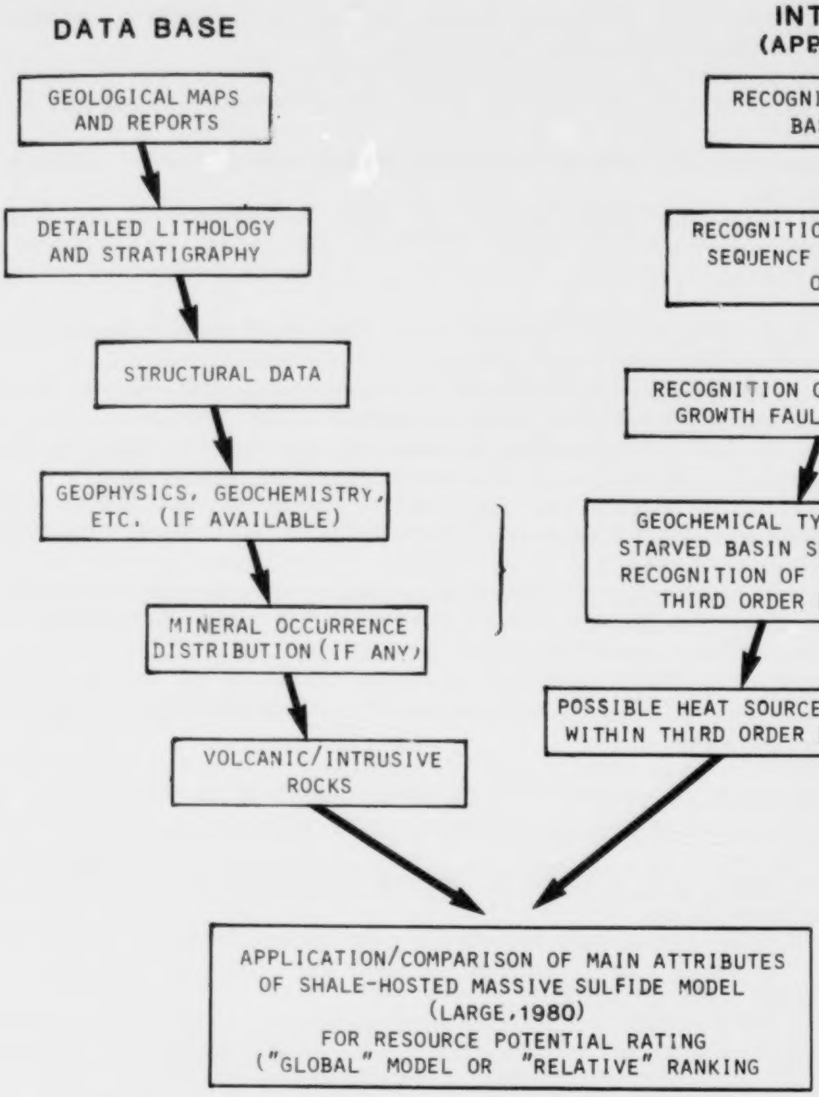
DATA BASE
INTERPRETATION (APPLICATION SENSE)
GEOLOGICAL MAPS AND REPORTS
DETAILED LITHOLOGY AND STRATIGRAPHY
STRUCTURAL DATA
GEOPHYSICS, GEOCHEMISTRY, ETC. (IF AVAILABLE)
MINERAL OCCURRENCE DISTRIBUTION (IF ANY)
VOLCANIC/INTRUSIVE ROCKS
RECOGNITION OF RIFT-BOUNDED BASIN (FIRST ORDER)
RECOGNITION OF "STARVED BASIN" SEQUENCE AND POSSIBLE SECOND ORDER BASIN
RECOGNITION OF POSSIBLE GROWTH FAULT SYSTEM
GEOCHEMICAL TYPING OF STARVED BASIN SEQUENCES; RECOGNITION OF POSSIBLE THIRD ORDER BASIN
POSSIBLE HEAT SOURCE NEAR/ WITHIN THIRD ORDER BASIN
APPLICATION/COMPARISON OF MAIN ATTRIBUTES OF SHALE-HOSTED MASSIVE SULFIDE MODEL (LARGE, 1980) FOR RESOURCE POTENTIAL RATING ("GLOBAL" MODEL OR "RELATIVE" RANKING

FIGURE 10.—Correlation of geoscience data and deposit attributes in the northern Baffin Island rift zone.

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MINERALS IN NATIONAL FOREST MANAGEMENT

By J. Lamar Beasley
U.S. Forest Service

INTRODUCTION

I am very pleased to be here today, and I am particularly pleased to see a joint meeting of the Geological Survey of Canada and the U.S. Geological Survey. I think that we have a great deal of knowledge and many techniques that our two countries can share, so that we can both manage our abundant mineral resources more efficiently.

I cannot think of any two countries that have had a better relationship over the last two centuries. We have enjoyed common borders and traditions. More often than not, we have shared common viewpoints on many major political issues and the vision of the life that we want for our peoples. In natural resources, we have also shared many concerns, from mutual problems of fire and insect outbreaks to a shared appreciation for the abundance of natural resources that we have both been blessed with.

I know that several other speakers will focus more on how our two nations can work together even more closely in the future. So, let me focus on my topic of consideration of minerals in national forest management.

IMPORTANCE OF THE NATIONAL FOREST SYSTEM

The National Forest System is of major importance to the U.S. economy and to our citizens. The national forests cover more than 190 million acres of public land, an area more than seven times the size of the State of Virginia, in which we are now meeting. These lands:

oAre the storehouse of about half of the softwood sawtimber in the United States.
oProvide habitat for nearly 60 percent of the animal species in the United States.
oFurnish three-quarters of the West's water supply and quite a bit of the East's.
oAre the biggest single supplier of outdoor recreation in this country and contain 32 million acres of designated wilderness.
oContain an estimated one-quarter of our Nation's potential energy resources.
oHold unique deposits of some critical minerals (for instance, they produce about 14 percent of the world's lead and nearly a quarter of its molybdenum).

The national forests are also vital to local and State economies. In 1984, for instance, receipts from the National Forest System brought $1.18 billion into the Federal Treasury; under law, 25 percent of those receipts was returned to State governments for public schools and roads in counties where the national forests are located. The rents, royalties, sales, and bonus bids for minerals alone brought receipts of $136.4 million, about $34 million of which were returned to the States.

Given such diverse resources and public benefits, it is no wonder that we are seeing more pressures on the National Forest System. These pressures, on the one hand, call for more intense exploration for oil, gas, and minerals. On the other hand, there are more pressures and more laws to ensure that mineral exploration and development are done in concert with surface resource protection.

HISTORY OF MINERALS MANAGEMENT IN NATIONAL FORESTS

Minerals management in the National Forest System has changed a great deal over the last century. We have really seen two distinct eras of minerals management. The first began in 1872, when Congress passed the act that governs exploration and mining on Federal lands. From that time until about the early 1960's, minerals management emphasized accommodating the miners' needs while protecting and managing surface resources as the law and policies would allow. The United States had a surplus of natural resources, so minerals were developed wherever they were found, with relatively little regard for the surface resources.

The second era in minerals management began in the early 1960's and has continued to the present. It marked major changes in philosophy about management of our Federal lands. We started hearing a great deal from the public about environmental protection, surface management, and legislative designation of lands for specific purposes. Within 20 years, we saw more major changes than we had during the 90 previous years.

We saw a whole spate of new legislation: The Wilderness Act, the Wild and Scenic Rivers Act, the National Environmental Policy Act, Water Pollution Control Act Amendments, the Endangered Species Act, the Forest and Rangelands Renewable Resources Planning Act, the National Forest Management Act, the Surface Mining Act, and the Clean Air Act Amendment. These acts, along with others, were responsive to public pressure to recognize environmental values more clearly and, in the case of the national forests, to manage lands in ways that would protect these values.

By the early 1970's, we began taking a closer look at how mining was affecting surface management and asking how we could do a better job of accommodating mineral development while protecting other resources. As a result, the U.S. Forest Service (USFS) developed the surface mining regulations of 1974. We still consider these regulations a giant step forward in managing for total resources.

FOREST SERVICE MINERALS RESPONSIBILITIES

Let me briefly review the role of the USFS in managing minerals in the National Forest System.

The USFS and the U.S. Department of the Interior share responsibility for regulating and managing mineral activities in the National Forest System.

The USFS controls surface resources, and the Department of the Interior manages actual mineral resources. In actuality, we work together to ensure that mineral development and surface resource use are in harmony.

Under the 1872 mining laws, any U.S. citizen can stake a claim to certain hard-rock minerals on public domain lands. The USFS administers operations on mining claims in the National Forest System by requiring operators to submit operating plans, which include provisions for reclamation. The 1872 mining laws do not apply to acquired lands, but other laws basically authorize leasing of hard-rock minerals on these lands.

Other commodities, such as oil and gas, are covered under the Mineral Leasing Act of 1920. For leasable minerals, the USFS recommends whether the Department of the Interior should issue the leases, with surface resource stipulations.

Our objective is to encourage orderly exploration and development of mineral resources while protecting surface resource uses.

INTERCHANGE WOULD FACILITATE MINERALS MANAGEMENT

The USFS may have even more direct authority over minerals in national forests in the near future. Last January, the USFS and the Bureau of Land Management (BLM) proposed an interchange of lands and minerals management responsibility. The goals of such an exchange are to improve public service and efficiency and to cut costs. Under the interchange proposal, each agency would have total authority over both surface and subsurface resources on lands under its jurisdiction.

In the area of leasable minerals (such as oil, gas, and a few solid minerals such as sulfur and coal) the exchange would formalize arrangements that have been in place informally for many years. Since 1945, the USFS has handled the preleasing work and has recommended whether a lease should be granted, as well as suggesting surface resource protection stipulations to the BLM. In spite of our best efforts to streamline the process, some duplication of effort and delays do result.

For locatable, or so-called hard-rock, minerals, mining claims are referred to the USFS for review before the BLM validates them. For many years, the USFS has had its own regulations requiring that operating plans for mining operations protect surface values.

Likewise, most mining operations affect other activities as well. They often require the use of roads and the building of structures. So, operators need USFS permits for off-lease roads, powerlines, and storage areas. Under the current system operators cannot avoid dealing with both agencies. Under the interchange, operators would have one-stop service.

Efficient minerals management is vital today, as exploration and development are intensifying. After the Arab oil embargo of 1973, it became very apparent that the United States needed to be more self-sufficient in the area of minerals. We are more than 50-percent dependent on foreign sources for a majority of critical materials essential to our economy and national security.

NATIONAL FORESTS: MINERALS STOREHOUSE

An obvious answer to our dependency problem was to tap the potential of the national forests. They are our major storehouse of minerals, particularly some that are strategic to national defense and energy needs.

Economic mineral deposits probably exist under the surface of about 5 percent of the National Forest System. The economic value of the minerals on that small portion of land may exceed that of all other resources combined. It is thus vital that we have accurate mineral assessments, so that we can develop the most appropriate sites and concentrate on the surface resources in the remaining areas. One of our major efforts involves integrating minerals management with the management of other resources. The way to meet as many of our needs as we can is through the forest land management planning system.

LAND MANAGEMENT PLANNING AND MINERALS

Minerals management is integrated into our land management planning for each national forest. Several years ago, we undertook a major project: writing a detailed and coordinated land management plan for each national forest and involving the public heavily in the development of those plans. So far, we have written 89 of the 123 plans needed.

I am convinced that minerals management is becoming a full partner in the planning process along with the management of timber, recreation, wilderness, wildlife habitat, water, and range grazing. However, as we manage minerals in a more planned way, we will need even better information than is now available about potential mineral deposits.

ACCURATE MINERAL ASSESSMENTS VITAL

As a basis for forest planning in the minerals area, we need good assessments from the U.S. Geological Survey (USGS). We already have some examples of what we consider excellent cooperation with the USGS and the U.S. Bureau of Mines (USBM). Their assessments were invaluable to the USFS and to Congress during the Second Roadless Area Review and Evaluation, which considered all National Forest System roadless areas for wilderness potential.

I think—and I know USFS Chief Max Peterson agrees—that the USGS and the USBM have done a great job, especially given the large amounts of country involved, the inaccessibility of many areas, and the expense of obtaining subsurface data. All the work that they do is a matter of interpreting surface geology or, in some cases, doing a limited amount of subsurface work with special equipment.

I particularly hope that we will gain some valuable working tools from projects now going on in Colorado's San Isabel and South Dakota's Black Hills National Forests. There, the USGS is making its first efforts to collect data about mineral potential on a forestwide basis. Data have already been collected in the San Isabel, although the information has not yet been used in a forest plan.

We are looking forward to the completion of the Black Hills assessment, which should be in January. At the same time, the USBM is working on the economics of mineral resources in the San Isabel. The economic analysis, along with assessments of mineral potential, should give us a good basis for incorporating minerals resources more effectively into the forest plans. A joint meeting of all three agencies should determine how well the information can be incorporated into the planning process.

INTERPRETING THE DATA

Before we can use this information fully, we must interpret the data and place it in a context of land management and planning. Such a process involves:

oMaking observations about the quantity or quality of mineral resources.
oEstimating the relative importance of the geologic inferences in comparison with other potential deposits in the United States, especially strategic and critical mineral deposits
oAssessing the demand for the minerals.
oEstimating when these minerals might be economically mined.
oDeciding how these minerals would be transported.

After all these steps have been completed, we can more effectively manage the total forest resource, both mineral and surface. As you continue your meeting here, I hope that those of you from Canada will share any insights that you may have on making mineral assessments as useful as possible to land managers. I sense a great feeling of sharing here, and I hope that our two countries will work closely together on mineral issues in the future. Canada and the United States have, for many years now, cooperated in fire control, insect and disease suppression, and many other areas of forest management. Now, I hope that we can literally go below the surface and work closely together to explore new ways of making minerals assessments and management more productive and efficient for both nations.

A FEDERAL ROLE IN RESOURCE DEVELOPMENT IN NORTHERN CANADA

By G. N. Faulkner
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INTRODUCTION

I appreciate the opportunity to participate in this seminar and to share with you the view of the Department of Indian Affairs and Northern Development (DIAND) on the evolving role of the Government of Canada in Canada's North, particularly with respect to mineral and hydrocarbon development.

The North, as we define it (fig. 1), is that 40 percent of Canada lying north of latitude 60°, comprising the Yukon Territory and the Northwest Territories. It is Canada's last frontier, sparsely populated by only 73,000 people, some 48 percent of whom are of native origin. The North is emerging as an important region, both because of its immense resource potential and because it is one of the world's last unspoiled landscapes. It took man nearly 10 centuries to thread his way through the Arctic Islands. Today, the jet aircraft crosses the Arctic in several hours. Such a flight across the northernmost lands brings home a vivid truth about the nature of the North.

The northern landscape is varied. From the Mackenzie River Delta to Churchill on Hudson Bay, the waivering tree line separates the tundra from the boreal forest. The North is the tabletop monotony of the barrens, the dramatic pinnacles and fjords of Ellesmere Island, and the rolling tiaga forest of the Yukon. In the Arctic Islands, July temperatures rarely reach 50°F, and, on dark winter nights, the northern heavens may take on the fluorescent colors of the aurora borealis. The vast whiteness of the Arctic when the wind stirs the air and snow into featureless nothing belies the fact that the high Arctic is a frozen desert.

In this paper, I hope to present a picture of the evolving economic and social development of the North as it relates to resource development and government participation in the process. The public lands and water of the North and their contained resources are under the purview of the Government of Canada. The central responsibility for administering nearly all northern land, water, and forests rests with DIAND. Some 38 other Federal agencies operate in the North, both because of other specific legislation and because the provision of certain services is the responsibility of these agencies.

A number of administrative responsibilities have devolved to the two Territorial governments. In the past two decades, for example, the Government of the Northwest Territories has evolved from a small, federally provided civil service to a full-fledged, viable northern government whose structure parallels that of the Provincial governments. On the constitutional side, the former small, partially appointed Northwest Territories Council has evolved into an elected legislative assembly, the members of which are predominantly of native origin. However, the Territorial governments have not yet gained Provincial status as full members of the Canadian confederation. The Northern Affairs side of DIAND has the fundamental objectives of fostering the political, economic, and social development of the North, and the two levels of government continue to move toward further devolution. The dynamics of change in the North today and related public land management have to be understood in terms of political evolution, aboriginal rights and land claims, economic development, and resource management.

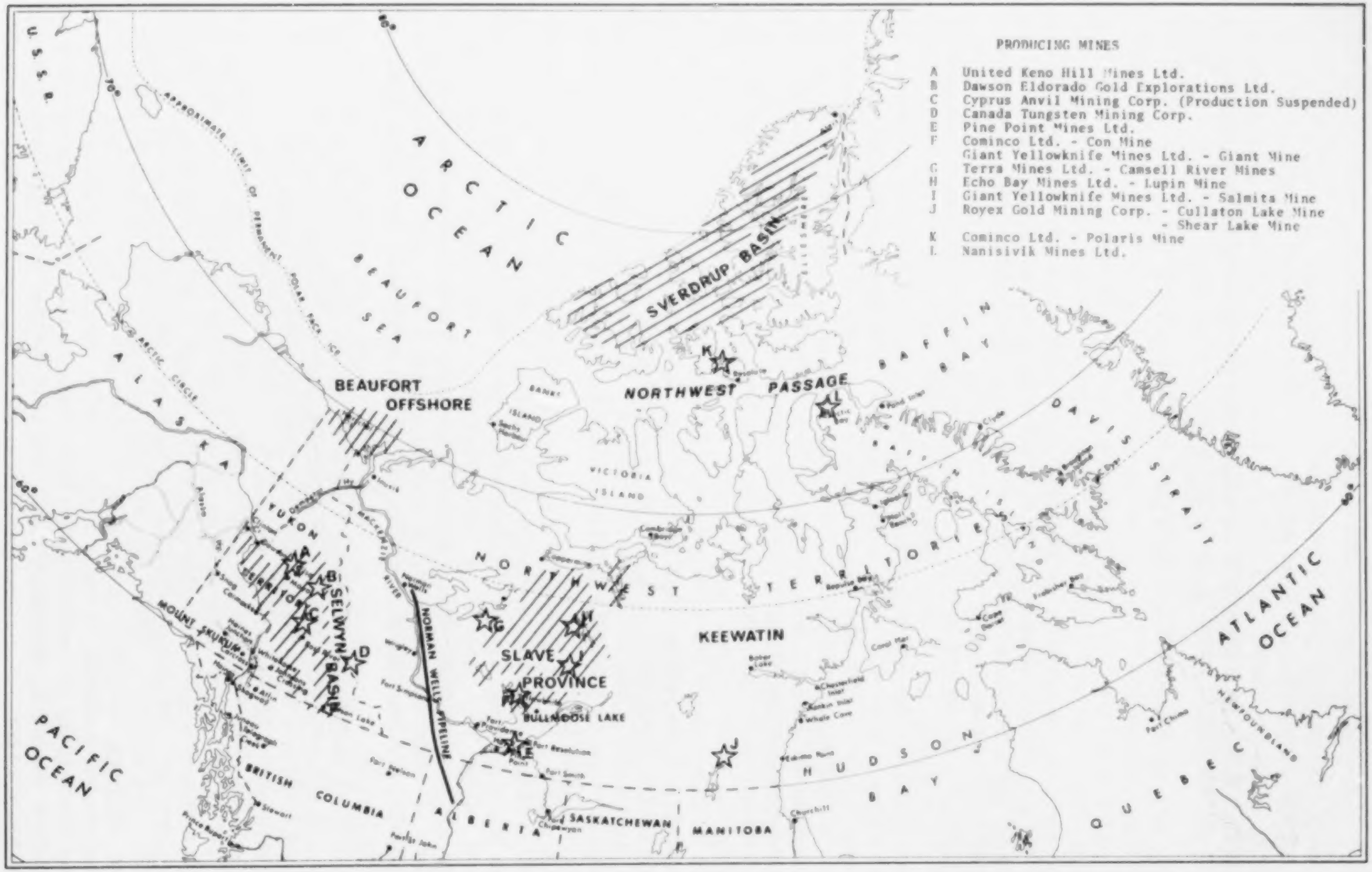
PRODUCING MINES
A United Keno Hill Mines Ltd.
B Dawson Eldorado Gold Explorations Ltd.
C Cyprus Anvil Mining Corp. (Production Suspended)
D Canada Tungsten Mining Corp.
E Pine Point Mines Ltd.
F Cominco Ltd. - Con Mine
Giant Yellowknife Mines Ltd. - Giant Mine
G Terra Mines Ltd. - Camsell River Mines
H Echo Bay Mines Ltd. - Lupin Mine
I Giant Yellowknife Mines Ltd. - Salmita Mine
J Royex Gold Mining Corp. - Cullaton Lake Mine
- Shear Lake Mine
K Cominco Ltd. - Polaris Mine
L Nanisivik Mines Ltd.
U.S.S.R.
70°
60°
ARCTIC OCEAN
APPROXIMATE LIMIT OF PERMANENT POLAR PACK ICE
BEAUFORT SEA
ARCTIC CIRCLE
ALASKA
BEAUFORT OFFSHORE
SVERDRUP BASIN
NORTHWEST PASSAGE
BAFFIN BAY
DAVIS STRAIT
BANKS ISLAND
VICTORIA ISLAND
YUKON TERRITORY
MACKENZIE RIVER
NORTHWEST TERRITORIES
SELWYN BASIN
MOUNT SKUKUM
NORMAN WELLS PIPELINE
SLAVE PROVINCE
BULLMOOSE LAKE
KEEWATIN
HUDSON BAY
QUEBEC
NEWFOUNDLAND
ATLANTIC OCEAN
PACIFIC OCEAN
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA

FIGURE 1.—Map of Canada showing locations of principal petroleum basins and mining districts.

Considerable exploration and development work over the past two to three decades has partially revealed the mineral and energy resource base. With respect to hydrocarbons, about one-third of the North is composed of sedimentary basins, which in volume are twice the dimension of the interior platform of the western Canadian provinces (1.7 million cubic miles as opposed to 0.8 million cubic miles). The current estimate of proven northern oil reserves is 1.5 billion barrels of crude oil, and proven gas reserves stand at 24.5 trillion cubic feet. These proven reserves are thought to represent about 13 percent of the North's total expected petroleum resource potential and 17 percent of the gas resource potential[1]. These resources are largely concentrated in the Mackenzie Valley and Delta and in other regions of Canada's Arctic Archipelago[2]. In spite of the dimension of discovered hydrocarbons, the process of resource definition is ongoing. Almost all of the hydrocarbon resources remain to be developed and linked by suitable transportation to markets.

Identified hard-mineral resources are more difficult to quantify in simple numbers because of the commodity mix. But, to give you an idea of historic production, the North has produced some 743 tonnes[3] of gold and 8,577 tonnes of silver, primarily from four mining areas. Base-metal production has amounted to 8.24 million tonnes of metal,[4] and asbestos some 0.9 million tonnes.

One of the North's greatest mineral resources domains is in the Yukon's Selwyn Basin, where two of the world's largest tungsten deposits are situated--the Cantung Mine and the Mactung scheelite deposit. About 60 million tonnes of high-grade tungsten ore have been outlined in these deposits and an additional 9 million tonnes in other deposits.

The Selwyn Basin also hosts a number of sedimentary exhalative zinc-lead deposits, of which only Cyprus Anvil's Faro deposit has so far been brought into production. In total, the basin contains an identified 615 million tonnes grading 7 percent combined zinc and lead or better. The resource potential of the basin has been estimated at 900 million tonnes of economic and subeconomic zinc-lead resources.

In Slave Province, north of Great Slave Lake, over 40 million tonnes of rich base-metal sulfide resources in stratiform deposits have been identified in Archean Yellowknife Supergroup volcanic belts. Examples are the Bathurst Norsemines (Hackett River) and Izok Lake zinc-lead-copper-silver deposits. These base-metal resources are yet to be developed for production because of the need for economic land transportation to these remote sites. In the Northwest Territories, Mississippi Valley-type deposits contain identified resources of 137 million tonnes grading 5 percent combined zinc-lead or better. A large proportion of this resource is presently being mined at the Pine Point, Nanisivik, and Polaris mines, where rail and marine transport have allowed development. The same Yellowknife Supergroup in Slave Province that hosts base-metal sulfide deposits also hosts most of the identified lode gold resources of the North. The most important and productive lode gold deposits have been found in the Yellowknife camp and in the Contwoyto Lake area. Slave Province also contains the Thor Lake beryllium deposit, which could well become a leading world source of beryllium.

The undeveloped coal and iron ore resources of the North amount to at least 30 billion and 8 billion tonnes, respectively. Other regions of the North host important uranium, silver, copper, and molybdenum deposits.

The northern mining industry has disproportionate economic importance in comparison with its size. The industry today is comprised of some 13 hard rock mining centers (establishments) and 150 Yukon-based placer gold operations. The mineral industry has for a number of years been the leading nongovernmental sector of the northern Territorial economies. In 1984, the value of metallic mineral production was some $790 million (Canadian dollars), and the industry directly employed 3,200 people (13 percent of the work force).[5] Production of sand, gravel, and stone accounted for an additional $51 million.

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[1] On the basis of a 50-percent probability estimate.

[2] Mainly the Sverdrup Basin.

[3] Tonnes are metric tonnes containing 32,151 troy ounces.

[4] Including 2.89 million tonnes of lead, 5.29 million tonnes of zinc, and 0.13 million tonnes of copper.

The output per northern mine far exceeds the average of mines located in the Provinces because of the size and tenor of economic northern deposits. In the Northwest Territories, for example, Echo Bay's Lupin Mine has become Canada's second largest gold mine; 1984 production was 5.6 tonnes out of a total of 12.4 tonnes for all of the Northwest Territories and 81 tonnes for Canada as a whole. The northern mining industry shipped 75 percent of Canada's tungsten output, 32 percent of the lead, 28 percent of the zinc, and 19 percent of the gold.

Expenditures on hydrocarbon exploration and development were close to $1 billion in 1984. The fledging oil and gas industry accounted for only $20 million of production at imputed wellhead prices in 1984, but this figure will increase significantly in 1985 because of new production, which commenced in May this year at a rate of 28,000 barrels per day, from the Norman Wells oil field on the Mackenzie River. The outlook for new oil and gas development over the next few years is good.

Both the northern mineral and petroleum industries are in an early stage of development, and, although the outlook for mining development has been dimmed by continuing weakness in the mineral market, it is expected that resource development will continue to be the key to economic growth in the North.

EARLY MINING DEVELOPMENT

A brief review of historical development will give you a better understanding of the Federal Government's role in the North and even of the participation of the Government of the United States of America.

The government's involvement in the North followed the early explorations of furtraders, expeditions from Great Britain in search of the Northwest Passage, and early whaling expeditions to Arctic waters. In 1870, Great Britain transferred to Canada the immense territory, chartered to the Hudson's Bay Company, called Ruperts Land and the mainland Northwest Territories. Two years later, the Dominion Lands Act was passed by Parliament to provide for the administration of the Northwest Territories. The Yukon Territory was created in 1898, the year of the historic Klondike gold rush. The discovery of the Klondike gold field completely changed conditions in the hitherto unorganized and almost unknown Yukon District. Since 1898, placer mining has been the leading industry in the Yukon and has symbolized its spirit.

New provisions for the orderly disposition of mining lands in the Yukon were passed by Parliament in 1906 as the Yukon Placer Mining Act and in 1924 as the Yukon Quartz Mining Act.[6] Both Acts are still in force.

In the Northwest Territories, the first mine of any importance was established when brothers Gilbert and Charles LaBine opened the Eldorado radium-silver mine at Port Radium, on the eastern shore of Great Bear Lake, in 1934, a year before the discovery of gold at Yellowknife on Great Slave Lake and the subsequent founding of the Yellowknife gold camp.

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[5] An additional 700 people were employed seasonally in Yukon placer mining.

[6] Mining regulations to govern the disposal of quartz and placer mineral lands were passed by Order-in-Council in 1884.

The early history of mining in the Northwest Territories reveals the hands-on participation of pioneering members of the Geological Survey of Canada (GSC); both the Eldorado and Yellowknife discoveries can be credited in part to these pioneers. In 1900, J. Mackintosh Bell of the GSC reported cliffs stained with pink cobalt bloom nd green copper oxide on the shore of Great Bear Lake. Thirty years later, Gilbert LaBine discovered the Eldorado pitchblende on this site when he investigated the showing reported by Bell.

In 1935, Alfred W. Jolliffe, also of the GSC, set out to map the greenstone belt near Yellowknife Bay on Great Slave Lake. His party reported a gold occurrence on the western side of Yellowknife Bay. This information was released that summer and led to the staking of the first mine properties. One of these properties became Cominco's Con gold mine, which began production in 1938 and is still going strong.

In short, the GSC's early achievements in contributing to mineral discoveries in the Northwest Territories were outstanding.

As an aside, I want to mention the involvement in American history of the Eldorado Mine. During World War II, the mine became the leading supplier of uranium, a scarce and strategic resource.[7] Under a cooperative Canadian-U.S.-British agreement, the mine supplied radium to Enrico Fermi's historic atomic pile experiment at the University of Chicago to the secret Manhattan Project and the Los Alamos nuclear tests. America's wartime contribution to Canada's North was the construction of the 2,400-km Alaska Highway, the first road link from the Yukon to the south. During this period, the Norman Wells oil field supplied the newly constructed Canol Pipeline linking this Mackenzie Valley oil field to the Yukon and Alaska.

POST-WORLD WAR II ERA

Although gold mine development continued in the Northwest Territories following World War II, it was not until the mid-1960's that the mining industry experienced the beginning of its significant postwar growth and not until the late 1960's that the modern frontier's oil and gas industry got started.

In the immediate postwar years, much of the North was being discovered for the first time in a number of ways. In 1948, for example, James Houston hitched a free ride to the Arctic on a medical evacuation flight to an Inuit camp. He decided to stay and lived 12 years with the Inuit. During this period, he became a Northern Services officer and interested the Canadian Handicrafts Guild and the Department of Northern Affairs and Natural Resources (now DIAND) in Eskimo carvings. Thus began a new phase in the very ancient art of Eskimo stone carving and the the Eskimo or Inuit art industry as we know it today. The Canadian Handicrafts Guild and later the Federal Government fostered the commercial success of the industry. In recent years, Northern Affairs geologists have conducted fieldwork to outline new sources of carving stone for this industry.

The early postwar years also brought an awakened interest in and a coordinated Northern Development Policy for the northern peoples, following a period of neglect during the 1930's and the war years. The welfare of the northern peoples improved remarkably through health, education, and housing services. Measures were taken to build a new economy incorporating wage employment and case earnings, so that the fur trade would not be the only source of income. The objective was to enable northerners to share fully in the national life of Canada and to enjoy the same benefits as other Canadians.

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[7] Because of the strategic importance of uranium to the Allied war effort during the later stages of the World War II, the mining company was expropriated under willing terms by the Federal Government from 1943 to 1944. Canada's great (American-born) wartime Minister of Munitions, C. D. Howe, was instrumental in the Government's decision to purchase all shares of Eldorado.

During the second half of the 1950's, the only new mine development was the Rankin Inlet nickel-copper mine on the western coast of Hudson Bay. This operation was unique, because it was the first sizable mine to rely on Inuit workers. When the ore was exhausted in 1962, the mine settlement became one of the first Arctic communities to be permanently occupied by the itinerant Inuit hunting and fishing people. There was a need to bring people together, particularly since, during the early 1950's, starvation had spread across inland Keewatin District in the eastern Northwest Territories. The Inuit settlement was the beginning of modern acculturation to the ways of southern Canadians, particularly through conventional education and trade skills provided for both the young and the older generation. Some mistakes were made in the Government's effort to help northerners, but never again would the North be neglected.

The 1960's represented a decade of road and railway development in support of mine development and new policies. In 1961, under a thrust for modern development, the Government amended the Canada Mining Regulations of the Northwest Territories to encourage mining investment. The royalty regime provided a 3-year royalty-free period,[8] and, at that time, the Canadian Income Tax Act provided a similar 3-year tax-free period. This period was the halcyon days of mining taxation. During the same year, promulgation of the Canada Oil and Gas Land Regulations created a favorable investment climate for hydrocarbon exploration. From 1965 onward, the Federal Government's Northern Roads Program was accelerated. In the Northwest Territories, also during 1965, the newly completed Great Slave Lake Railway extending to Great Slave Lake carried the Territories' first zinc-lead concentrate from the Pine Point mining camp to markets. In the Yukon, the discovery of the Faro zinc-lead deposit in 1965 and its opening in 1969 led to the beginning of massive systematic exploration and a quantum jump in the Yukon's mineral production value.

PROVISION OF INFRASTRUCTURE AND SUPPORT FOR MINING

The Federal Government's role in providing transportation and electrical power infrastructure in support of northern mining and petroleum development has varied as Government objectives have changed. Most public investment has been made on a pragmatic case-by-case basis. The $76 million provided by the Government of Canada for construction of the Great Slave Lake Railway was invested in part to open the Pine Point lead-zinc district and in part as a regional development project to provide transport linkage between the transcontinental rail system and the Mackenzie waterway to the Arctic. The Pine Point Mine's concentrate provided the rail traffic to support this important northern transport corridor.

In 1969, the Yukon's territorial highway system was extended in support of the opening of Cyprus Anvil's Faro lead-zinc mine. This mine was the most important employer and economic asset in the Yukon until metal prices forced its closure in 1982.

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[8] The 3-year royalty-free provision for new mines is still a provision of the Canada Mining Regulations, but the Federal Income Tax Act was amended in the early 1970's to rescind the 3-year income tax provision.

In the past 2 years, DIAND's Northern Program has put an enormous amount of work into getting the Faro Mine back into operation. A 2-year, $50 million overburden stripping program at Cyprus Anvil was financed by both Federal and Territorial governments and by the company during 1983 and 1984.

Another project was the Dempster Highway, which was constructed from near Dawson in the Yukon to the MacKenzie Delta. It was originally started under the Federal Government's "Roads to Resources Program" in the early 1960's but was not completed until 1979. The highway provides an important linkage to the Arctic, especially for hydrocarbon development in the Mackenzie Delta-Beufort Sea region.

In the Arctic Archipelago, the Federal Government, in pursuit of a number of policy objectives, negotiated the development of the Nanisivik Mine, which opened in 1976 as our first Arctic Island mine.

In return for public infrastructure investment (dock, road, town site, and airport), provision was made for cost recovery and an 18-percent Government equity interest in the mine project. The project provided northern employment and advanced Arctic mining and shipping technology and has proven to be a highly successful operation. The trend, in recent years, has been toward cost recovery on public infrastructure investment, but each project is examined on its merits and with a view toward public benefits.

Unlike the Siberian regions of the Soviet Union, where major rivers flow north to the Northeast Passage, the Canadian Arctic mainland is a barrier to easy transport because only one major river (the Mackenzie) flows northward to tidewater. Also, land distances over the mainland tundra can be a barrier for economic land transport of lower value bulk mineral commodities such as base-metal concentrate. Yet, most of the mainland region of the Northwest Territories is part of the Canadian Shield and has an important potential for mineral development. In the Arctic Islands, access by marine transportation through the Northwest Passage is possible, as it is in the Northeast Passage of the Soviet Union.

Infrastructure, including transportation and, in some cases, electrical power facilities, is a key consideration for northern mine development. Some companies in the North own their own electrical power facilities, and others are supplied on a full-cost basis by the Northern Canada Power Commission, a Crown corporation. The pronounced trend in community development since the mid-1970's has been away from the traditional mining town to more economic, and perhaps more accommodating, fly-in fly-out operations. The newer mines in the Arctic, the Polaris Mine on Little Cornwallis Island, the Lupin Mine on the northern mainland, and the Nanisivik Mine on Baffin Island are all connected to southern urban centers by fly-in fly-out rotation of personnel. The Lupin and Cullaton Lake gold mines were developed by airlifting material and supplies to the mine sites. A record was set when over 21,000 tonnes of material was flown by Hercules aircraft to the Echo Bay mine in 1 year. The cargo included grinding mills, oil fuel tanks, and other large items. The nearest road and railway are at least 1,000 miles to the south of the Polaris and Nanisivik mines, which are supplied by sea and air transport. At the Polaris and Lupin Mines, company-owned housing is comprised of modern modular units and recreational facilities enclosed for protection against the vigorous climate.

Perhaps one transport mode, which is not new but is nonetheless very important in mine development and production, is the seasonal winter road, or ice road, which extends over the tundra and frozen lakes. Last winter, two gold mines and a number of exploration-development projects in the Northwest Territories were served by such roads, including one that extended 400 miles from the Lupin Mine to Yellowknife and carried some 700 truckloads of fuel and supplies. Similar roads are used in the Soviet Union.

Above the tree line, the main obstacles to mine development are of a technical and logistical nature. Ingenuity, know-how, good teamwork, and diligent skilled personnel are a must. Cominco developed its Polaris Mine during 1980 and 1981 by a major airlift of supplies and by flotation of a barge-mounted mill complex by sea from Trois Rivieres, Quebec, to Little Cornwallis Island. The airlifting of the Lupin Mine and mill complex in 1981 was also a major engineering accomplishment. The stockpiling of lead-zinc concentrate at Polaris and Nanisivik for most of the year and its shipment, over a several-week Arctic shipping window have been a new, challenging solution to a unique Arctic transport problem.

In the Beaufort Sea and High Arctic Islands, hydrocarbon exploration has called for similar solutions, such as the development of construction techniques for building ice-drilling platforms and artificial-island drill platforms. Also, ice-class drilling ships and barges have been pioneered in the northern offshore.

HIGH ARCTIC DEVELOPMENT

The first resource development effort in the Arctic occurred more than 400 years ago, between 1576 and 1578, when Martin Frobisher mined "fool's gold" or pyrite in the southern Baffin Island area. In 1876, an American Lieutenant, W. A. Mentzer, mined 15 tonnes of mica in the Cumberland Sound area of Baffin Island. His interest in mining the area led Great Britain to transfer to Canada, in 1880, the Arctic Island possessions not previously annexed to Canada. Hence, as early as 1876, resources were part of the geopolitical environment of the North and of colonial diplomacy.

In 1911, Joseph Bernier sailed into the eastern Arctic at the head of one of a number of Dominion Expeditions, sponsored by the Government of Canada, to provide a base for effective occupation. A prospector in the party reported mineralization near Strathcona Sound on northern Baffin Island. In 1937, two prospectors, J. F. Tibbitt and J. W. McInnes, made a remarkable journey from Churchill to Strathcona Sound to explore the mineralization reported by Captain Bernier. It was not until 1958, however, that the Nanisivik zinc-lead-silver deposit was indicated by drilling. In 1956, before the drilling of the deposit, Robert G. Blackadar of the GSC reported lead-zinc mineralization, which later proved to be part of the Nanisivik ore deposit and the reason why geologists from Texas Gulf Sulphur Co., Ltd., investigated the area.

In 1967, Panarctic Oils, Ltd., a public-private sector consortium, was formed to explore for oil and gas in the Arctic and to establish Canadian sovereignty. Two years later, news of the gigantic Prudhoe Bay oil field on Alaska's forbidding North Slope electrified the petroleum industry and stimulated hydrocarbon exploration in the Mackenzie Delta-Beaufort Sea areas. The energy crisis in the 1970's further accelerated exploration activity in the remote northern sedimentary basins.

The concern over potential massive oilspills in the Arctic marine environment came to the fore during the test voyage of the very large crude oil carrier Manhattan through the Northwest Passage in 1969. One month before the voyage, two barges bringing supplies to Panarctic Oils' Arctic exploration base on Melville Island were crushed by ice and sunk in the Northwest Passage. The question of a large oilspill became more critical when ice in Lancaster Sound knocked out a huge panel of the Manhattan's hull during the return voyage (west to east) and spilled 15,000 barrels of ballast water. In response to the environmental threat, Parliament passed the Arctic Waters Pollution Prevention Act in 1972, governing the design and pilotage of vessels in the navigation of the Canadian Arctic.

Since the mid-1970's, Canada's role in Arctic shipping has been strengthened. The opening of the Nanisivik Mine in 1976, on the southern side of Lancaster Sound, led to construction of the MV Arctic, an Arctic Class 2 bulk carrier.[9] Both projects involved

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[9] Class 2 means that the ship can navigate safely and steadily through 2 ft of ice.

Federal Government participation (in the form of equity investment) because of a number of policy objectives, such as advancing both Arctic mining and shipping technology.

In 1979, the Government of Canada and Cominco, Ltd., reached agreement for the development of the Polaris Mine on Little Cornwallis Island, north of Barrow Strait on the Northwest Passage. The Polaris Mine project served the same policy objectives mentioned earlier.

In recent years, the MV Arctic was chartered to carry most of the lead-zinc concentrate produced by the Nanisivik and Polaris Mines through the eastern part of the Northwest Passage. The total mine output amounts to some 400,000 tonnes of lead-zinc concentrate; in 1985, the MV Arctic will carry some 335,000 tonnes. Under Federal Arctic shipping policy and negotiated mine development agreements, Nanisivik is obligated to use Canadian flagships, if they are reliable and competitively priced. The Polaris Mine is obligated to use the MV Arctic for at least 50 percent of its concentrate shipments. Both companies have exceeded their requirements.

There is still concern over possible oilspills in Arctic waters, both from offshore development and from tanker transportation, since the eastern part of the Northwest Passage is rich in marine life. It is also relatively ice free during several weeks each year, although ice conditions become more difficult west of Cornwallis Island.

The Arctic Pilot Project, conceived by Panarctic Oils, Petro Canada, and other firms, has been proposed to ship liquefied natural gas (LNG) by icebreaking carrier from the huge Sverdrup Basin gas fields. As yet, a demonstration of icebreaking LNG transport technology has not been made.

Today, demonstration icebreaking voyages combined with satellite imagery for navigation give us the means to test environmental impacts. This summer, Panarctic Oils made a demonstration voyage using the MV Arctic to ship 100,000 barrels of oil from the Bent Horn Field on Cameron Island to the eastern Canadian market. This shipment of crude oil from Canada's Arctic and offshore regions was the first of its kind. Panarctic estimates its reserves at 17.3 trillion cubic feet of natural gas and some 250 to 500 million barrels of recoverable oil.

THE 1970'S TO THE PRESENT: A DECADE OF CHANGE

Since 1970, the variety and complexity of northern issues to be addressed by the Federal and Territorial governments have increased remarkably. Interest groups have also been more vocal. In response to the issues, Territorial governments have gained a greater influence over the course of northern development. Hence, the North is no longer viewed as being completely within the purview of the Federal Government but as a region of joint and cooperative administration. Also, by the late 1970's, as serious resource and land use conflicts emerged, it was obvious that the Federal Government's ad hoc approach to land and resource management was not satisfactory.

Since 1973, the Federal Government has negotiated native land claims involving aboriginal rights with the four northern groups of native people. The first claim was settled in 1984, when an Act of Parliament gave COPE (Committee of Original People's Entitlement) the resources that will allow the Inuvialuit people of the Beaufort Sea region to be a major participant in western Arctic development. Negotiations with the other three claimant groups—the Tungavik Federation of Nunavik, the Dene and Metis (of the Mackenzie Valley), and the Council of Yukon Indians—are not yet complete. These four groups represent about 48 percent of the northern population. Settlement of the major issues involved in some of these claims is expected to shape the future of the

North and, in particular, the means by which native peoples can participate fully in that future. This participation is especially important as land is given over to industrial activities and native economies are displaced. Despite the changes in traditional social and cultural norms since contact with southern culture, northern native values persist and inform the responses that people make to present day circumstances.

Several pieces of legislation have been passed by Parliament to address public concern over the environmental issues that emerged by 1970. As it had in Alaska, the issue of placer gold mining versus protection of water habitats and fisheries became a major issue. Amendments to the Fisheries Act in 1969 and 1977 increased environmental pressure on the Yukon placer gold mining industry. Following the passage of the Northern Inland Waters Act in 1972, the Yukon placer mining industry became subject to requirements of the Act. DIAND is still working on appropriate mechanisms and environmental standards with the Federal environmental departments, the Government of Yukon, and interest groups to finally resolve this issue.

In 1971, the Territorial Land Use Regulations were brought in to mitigate the environmental effects of land use activities related to exploration for oil and gas and minerals. Recently, a new Northern Land Use Planning process has been drawn up for the Northwest Territories, but it has yet to be approved in the Yukon. Its purpose is twofold: to replace a largely ad hoc approach to development and resource management with a systematic approach and to replace a project-specific, reactive approach with an anticipatory one. The planning process brings closer together resource development, traditional land use, and conservation interests by providing a means of integrating and coordinating the goals and objectives of all participants, including the general public. The process allows all potential uses within a given area to be considered and compared with one another simultaneously.

The environmental constraints and reviews imposed by the Land Use Regional Environmental Review process and the Territorial Water Board's hearings have not proven to be burdensome for most mine developments. I believe that the processes in place have established credibility and respect among the different constituencies.

However, proposed northern megaprojects related to frontier oil and gas have been subject to more extensive public reviews because of their possible socioeconomic impacts, particularly with respect to traditional economies. Also, there is the question of potential major environmental damage. During the 1970's, public concern in the North increased because of the ongoing large expenditures in Beaufort Sea-Mackenzie Delta hydrocarbon development and the prospect of a large-diameter oil pipeline along the Mackenzie River Valley. In 1974, the Mackenzie Valley Pipeline Inquiry was started under Justice Thomas Berger. Three years later, after extensive community consultation, the Berger Commission recommended a 10-year moratorium on the construction of the pipeline.

I am pleased to note the tremendous change in the climate for hydrocarbon development in the North among all constituencies. Because of the success of the consultation process, the North is ready for major hydrocarbon development. During 1983 and 1984, development of the Norman Wells oil field was increased by 200 production and water-flood wells, and a 25,000-barrel-per-day, 540-mile-long pipeline was constructed through the Mackenzie Valley to the south to link with southern markets. Production started in early 1985. This $896 million project brought significant benefits to northern people in the form of $100 million in contracts let to northern companies and wages of $33 million paid to northerners. During the planning and construction stages of the project, community involvement reached a new high, and the effect on the overall success of the Norman Wells expansion was beneficial.

Also in 1984, the Beaufort Environmental Assessment and Review Panel was conceived to review hydrocarbon activities in the Beaufort Sea-Mackenzie Delta region. The panel reported to the Federal Government during the same year. In broad outline, the panel's report cleared the way for commercial production and transportation of oil and gas from the Beaufort region. The panel recommended a small-diameter pipeline (20-40 in) capable of carrying up to 100,000 barrels per day. A larger pipeline may be needed for gas, so long as the socioeconomic impacts are no greater than those created by the oil line. The panel also called for a comprehensive public review if a large-scale (40-in) pipeline through the Mackenzie Valley were contemplated.

Currently, Polar Gas is proposing a $4.4 billion (36-in) pipeline to tap the gas reserves already delineated in the delta. ESSO Resources is also considering extending its Norman Wells oil pipeline northwest to the Mackenzie Delta. Gulf Canada is discussing the construction of a 20-in oil pipeline from the Beaufort Sea offshore and the Mackenzie Delta to southern markets. Finally, Panarctic Oils' Bent Horn has demonstrated that 100,000 barrels of crude oil can be shipped from Cameron Island to southern markets. Similar shipments could follow over the next few years.

It is clear that, although a number of the hydrocarbon megaprojects proposed for the North in the 1970's have not been realized, the door is open for commercial development. The Federal Government's budget of May 1985 and the Western (Energy) Accord have done much to create confidence in the Canadian petroleum industry, and investment has increased. The phasing out of the Petroleum Incentive Program grants in the North during 1986 and 1987 and the current downward trend in world energy prices could mean some deceleration in northern hydrocarbon exploration and development activities beyond 1987. However, as they have been in other frontier regions of the world, petroleum exploration and development will be largely geared to OPEC pricing and world energy markets. If demand and OPEC pricing hold and gradually strengthen, we will surely see major hydrocarbon energy development in the North.

The severe impact of weak world metal markets forced the closure of some mines in 1982. All but Cyprus Anvil's Faro Mine have reopened, and it may well be operational again soon. Since 1982, economic recovery has been substantial, and total mineral production value has increased. Also, a positive spirit of cooperation among unions, management, and other interested parties, including government, has successfully brought mines such as Pine Point, United Keno Hill, and Canada Tungsten back into production.

The Northern Affairs Program is working closely with Amax of Canada on planning the infrastructure for the future Mactung tungsten mine, one of the world's major tungsten deposits. Resumed growth in tungsten markets has made it possible to bring the site onstream on a favorable basis. We are also looking forward to the opening of new precious-metal mines now under development, such as the Bullmoose Lake gold deposit in the Northwest Territories and the Mount Skukum gold deposit in the Yukon. The pronounced expansion of the northern gold industry in recent years has contributed significantly to the regional economy.

LAND WITHDRAWALS AND MINERAL AND ENERGY ASSESSMENTS

As certain areas in Alaska have been, a portion of the lands in the Canadian North are closed to mineral exploration. Under the National Park Act, mineral and hydrocarbon exploration and development are prohibited in national park areas, which were selected because they were representative, notable examples of the diverse Northern landscape and its flora and fauna. To ensure that the creation of park lands does not tie up important mineral resources, the Federal Government, since 1979, has inventoried the mineral and energy resources of proposed park areas. These investigations are conducted before Ministerial decisions to withdraw a park area are made. Consultation with the Territorial governments, native groups, and interested members of the public (including the mining industry) is part of the process.

The GSC plays a major role in conducting mineral and energy resource assessments, or MERA's, as we call them. MERA's are conducted as both GSC-DIAND in-house studies and GSC field studies of mineral and energy resources. The published MERA reports form the basis for review of proposed park lands by the three Federal departments involved (Parks Canada of Environment Canada, DIAND, and the Department of Energy, Mines and Resources) and the Territorial governments. William Hutchison of Energy, Mines and Resources has referred to the MERA process, and at least two papers will be presented tomorrow by GSC officers on specific examples of the that process.

Northern land use issues and, in particular, the issue of alienation of public lands have been an important part of the Federal Government's policy development since the mid-1970's. As was the case in Alaska during the 1970's, mining interests are very sensitive about the restriction of public lands in the Canadian North. The perception is that, if x percent of the land is withdrawn, there is a corresponding reduction in the possibility of making a mineral discovery. Without the MERA process, this perception would be correct.

Nowadays, the total area reserve for northern national parks amounts to 3.8 percent of the northern land area. Parks Canada intends to expand the system by adding new parks, so that 5 percent of the North eventually could be park lands. Including other land areas, in which exploration and development are prohibited, the total area of prohibition amounts to 5.2 percent of the North.[10] Exploration and development are also prohibited on the 0.34 percent of the North set aside as freehold lands under the western Arctic Inuvialuit claim. These freehold lands could be opened for exploration and development under agreements negotiated with native corporations, similar to the Cominco-NANA, Inc., agreement on the Red Dog property in Alaska.

The GSC geologist has played an important role in the assessment of mineral resources on public lands in the North. Tremendous progress has been made in understanding metallogenic models and the metallogeny of particular mineral domains, such as the Selwyn Basin of the Yukon andh its important sedimentary exhalative zinc-lead deposits. Understanding of Canada's Archean volcanogenic polymetallic sulfide deposits has advanced remarkably in the past two decades. We have a number of good examples of such deposits in the Northwest Territories, and each year brings a wealth of new information on them. In this regard, the continuing research work of GSC geologists and other geologists will be important in assessing the mineral resources of public lands. Regional structural synthesis conducted by the GSC is also important.

As some examples of important GSC contributions, I would like to mention Dirk Templeman-Kluit's regional synthesis of the southern Yukon and his "tectonic mosaic" breakthrough, which gave us a modern view of the Yukon's geology. This work was part of a continuum, starting with the first Yukon Expedition in 1877 and spanning the years when Hugh S. Bostock made his important contributions there. Also in recent years, Don Norris has provided modern compilation maps and a similar modern synthesis of northern Yukon geology. Other GSC and Northern Affairs geologists have given us a good understanding of the mineral deposits and the resource inventory of the Yukon. Work of comparable quality, too extensive to mention, also has been done by the GSC in the Northwest Territories. Contributions to the assessment of hydrocarbon resources have been made by geologists of the Canada Oil and Gas Lands Administration and of the GSC. I believe that the work on geology and MERA assessments has been well done.

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[10] Activities may be restricted in the 2.8 percent of the North set aside for bird sanctuaries. Eventually, when native land claims have been settled and the northern national park system has been finalized, prohibited lands could approach or exceed 10 percent of the North. The final figure will depend on what areas are reserved for new parks and what areas become freehold lands through the settlement of native claims.

Within the Northern Affairs Program, geologic services divisions in both northern territories provide provincial-type geologic support for mineral exploration and some geoscience a computerized Northern Mineral Inventory, which would provide ready public access to the mineral resource data base for land use planning purposes and evaluation of mineral potential.

CLOSING NOTE

The North is Canada's last frontier and the last phase in building a confederation. Its future can be defined in terms of its people, lands, and resources. A strategic region, it contains an estimated 43 percent of Canada's hydrocarbon potential and possiblly 40 percent of its mineral potential. It is both a harsh and a fragile land, and we must be vigilant to preserve it. Its development has been relatively slow in comparison with that of northern regions of the Soviet Union, but its population is also much smaller. Although the number of sizable northern urban centers may never be large, we must plan so that the landscape will remain unspoiled and the quality of life for its people will continue. As resources are developed, there will be an ongoing need to maximize northern benefits and mitigate negative environmental impacts. The role of government in accelerating planning and research will be especially important with regard to land use planning and phased hydrocarbon development through demonstration projects. The northern mining industry is expected to show continued growth, since it has 40 percent of Canada in its backyard and a wide variety of geologic and metalliferous environments. Economic spin-offs from resource development activities will be realized both through direct participation of northerners and by provision of needed services.

PROBLEMS AND OPPORTUNITIES FACING THE MINERAL INDUSTRIES

By Hermann Enzer
U.S. Bureau of Mines

The past decade has been a difficult one for the domestic mineral and metals industries. Faced with saturated or even shrinking markets, they have simultaneously been confronted with increasingly strong competition from foreign producers, who have been further assisted by an exceptionally strong dollar. To make matters worse, the prices of many metals have hovered near depression-era lows, despite a robust economy.

JUST HOW DIFFICULT?

The combined impact of these trends on the mineral industries has been devastating. Many firms have operated at or near a loss in spite of the strength of the overall economy. A significant portion of their capacity has been curtailed, permanently shuttered, or even dismantled. Thousands of workers have been laid off or permanently furloughed; between 1981 and 1984, employment in metal mining alone declined by almost 50 percent. Despite deep cost-cutting programs and minimal capital spending, mining and metal firms have had to borrow extensively, so that their debt-to-equity ratios are now about 50 percent higher than the average for all industries. Given such conditions, there is little wonder why several large corporations with interests in mining and metals have put these interests up for sale, while other firms more fully committed to the business have attempted to redeploy at least a portion of their assets in other areas.

WHY?

But just what has been behind the problems of the mining and metals industries? Why have conditions changed so drastically? And what are the prospects for recovery, for a return to more "normal" times? Just about everyone in and around the minerals community has been asking these same basic types of questions.

At the U.S. Bureau of Mines, we, too, have been asking these same kinds of questions. And, probably like most other mineral analysts, we have developed our own list of problems afflicting the mineral industries these days.

But we have also looked beyond mining and metals and noticed that the same factors that have precipitated their problems seem to be confronting a broad range of industries in this country. Many other basic manufacturing industries (automotive, rubber, textile, basic chemical, and machinery) have also encountered difficult times. The difference is really one of degree, not kind.

Many have blamed the strength of the U.S. dollar, which, in effect, helps to improve the terms of trade of our foreign competitors. Although a strong dollar worsens the situation, we believe that there are a few fundamental megatrends (to borrow a phrase) at work that are significantly altering the course of major sectors of our whole economy. And, during any period of drastic change such as we are now experiencing, not only are substantial problems created, but so also are major opportunities.

THE GROWING INTEGRATION OF THE WORLD ECONOMY

Perhaps the most fundamental factor behind the problems of metals and other basic industries has been the increasing integration of the world economy through the growth of international trade. Since 1970, the total dollar volume of world trade has grown sevenfold. As a result, imports and exports now represent twice as large a portion of our gross national product as they did just 20 years ago, and today about 70 percent of the goods produced in the United States compete with merchandise from abroad. Stated simply, the U.S. economy is no longer a domestic one; rather, it is integrally linked with that of the rest of the world.

Because of this growing integration, more goods are being produced wherever they can be made the cheapest. And U.S. minerals and metals firms, along with several other basic manufacturing companies, have discovered that they face some major disadvantages in the emerging global marketplace.

THE COMPETITIVE DISADVANTAGE OF BASIC INDUSTRIES

Like many other basic industries, the mineral industries are largely capital-intensive, high-volume, continuous-process industries, and they tend to use standardized production processes in order to fully benefit from scale economies. These standardized production processes generally employ relatively simple skills that can be learned fairly readily by workers in developing countries. Furthermore, these workers can provide essentially the same quality and, increasingly, quantity of output for a small fraction of the wages paid to their counterparts in developed countries. Hence, those basic industries that use high-volume standardized production technologies and for which labor is a significant component of total costs are finding that developing countries frequently have a significant competitive advantage.

EVOLUTION OF THE POST-INDUSTRIAL ECONOMY

But, while metals and other basic industries seem to be beset by growing problems, the service, information, and knowledge sectors of the U.S. economy seem to be benefiting from expanding opportunities. In the aggregate, the service and information industries have long been growing faster than the goods-producing industries, and, by 1984, this sector had reached a position where it accounted for 68 percent of the gross national product.

SLOWING IN METALS DEMAND

The growth of the service and information industries has had a negative side effect on metals demand in the United States. Our use of steel, copper, and aluminum or, for that matter, of glass or basic chemicals is simply not increasing as fast as it did when our economy was dominated by heavy industry. At the same time, new information technology such as the microprocessor allows us to do things not only more effectively but also with less material. As a result of such trends, metals demand is now growing more slowly than the gross national product. And, in our economy, such a trend ultimately translates into below average returns on investment and, eventually, into a migration of capital to other products or industries.

REVOLUTION IN NEW TECHNOLOGY

Still, although the growth of the knowledge and information sector of the economy has contributed to lower metals demand, it has also led to the widespread technological changes that are currently taking place in so many areas. And in few places has technological change been any more dynamic and far reaching than it has been in materials. For, as a byproduct of the "knowledge" economy, materials science and engineering are becoming a coherent discipline and practice.

A new generation of advanced analytical instruments is enabling scientists to probe and study materials as never before. With the assistance of sophisticated mathematical models and powerful computers, materials scientists are gaining a much better knowledge of the composition of materials, which, in turn, is allowing them to design and control their properties as never before. Furthermore, on the users' side, equipment and devices increasingly require sophisticated materials specifically tailored to the functions to be performed. Hence, greater integration of design, performance, and processing requirements with materials properties and microstructures is occurring.

Because of such developments, intermaterial competition is increasing dramatically as polymers, glass, ceramics, metals, and composites seek those market niches for which they are ultimately best suited. But, although such competition seems to pose yet another series of problems for traditional commodity metal producers, it in fact represents a major opportunity for those metal companies that can quickly and effectively react and adapt to the opportunities created by the new materials competition. Indeed, it may well be that we are entering a new "age" of materials—one whose commercial growth potential may help to compensate for the depression and contraction occurring in heavy metals.

TECHNOLOGICAL CHANGE CREATES MAJOR NEW OPPORTUNITIES

Thus, in a period characterized by contraction, a change in perception is needed by mineral and metals producers if they are to recognize the opportunities created by the major changes that are occurring. The transformation from an industrial economy to a postindustrial one need not lead to a period of decline and ultimate extinction for basic industries. Rather, these industries must also ride the high-tech wave in order to grow competitive and survive in the global marketplace of today and tomorrow.

The mining and metals industries need to recognize that advanced technology represents opportunities that can be exploited rather than threats that must be evaded. Greater emphasis should be placed on developing increasingly specialized and sophisticated materials and more highly valued products that provide a quality advantage over the products of developing countries. Simultaneously, these industries must recognize the inevitable fact that labor costs will always be a handicap for U.S. basic manufacturing firms, particularly for commodity-goods producers using high-volume, standardized production technologies. Hence, highly advanced, fully automated production technologies that essentially eliminate the "man" from the assembly line will be needed if U.S. metals and other basic manufacturing firms are to complete in the world marketplace of the future.

Let me describe some of the more interesting developments occurring in materials today and perhaps shed some light on the opportunities that these developments represent for the mineral industries.

POLYMERS

After two decades of rapid growth following World War II, the production of polymers in the United States began to stagnate around 1970. Recently, however, interest in polymers has increased sharply, because advances in polymer technology have been accelerating. The principal impetus behind this resurgence has been the development of new polymer blends, materials that are analogous to metallic alloys. And, as they have with alloys, scientists can combine different polymers to produce new materials whose properties differ from those of their constituents.

Because polymers do not alloy as readily as metals, polymer blends were relatively uncommon until recently. New, more highly sophisticated analytical devices in combination with new polymer alloy manufacturing processes now enable scientists to reorder the molecular structure of polymers, so that they can obtain new materials that possess specific properties. As a result of such developments, plastics makers feel that they are entering a new period of rapid growth.

Polymer blends currently sell for about $1.50 a pound on the average. One research firm that closely follows the plastics market has forecast an average annual growth rate of 17 percent for these new materials through the year 2000. The total market for polymer blends amounted to $300 million in 1983, about a third of which was consumed in automotive and other transportation applications. Major producers of these materials include firms such as General Electric, Dupont, Celanese, and other major plastics producers.

CERAMICS

Ceramics include a wide range of inorganic, nonmetallic materials that not long ago were used largely in cement, bricks, glass, and pottery. Despite the routine commodity nature of most ceramic products, these materials possess a broad range of useful properties, including high heat resistance, special electrical and optical properties, and extreme hardness and wear resistance. Unfortunately, however, ceramics also possess one other notable property that has long prevented scientists from more fully exploiting their many attributes. That property, of course, is extreme brittleness.

Over the last several years, however, advancing materials technology has enabled ceramic scientists to gain better control over this failing and to design a whole new range of ceramic materials and products. The firms involved in this effort are referred to as the advanced ceramics industry. The new high-tech ceramic products generally are based either on the electrical properties of ceramics or on their structural properties of extreme hardness and resistance to high heat and corrosion. Hence, the high-tech ceramics industry has evolved into two separate segments: one that produces electronic components (for example, packaging of integrated circuits, capacitors, resistors, and so on) and one that produces engineered products and parts (for example, cutting tools, ball bearings, and nozzles).

Largely because of the fledgling nature of the advanced ceramics business, comprehensive information on the dimensions of the market is lacking. A recent study by the U.S. Department of Commerce estimated that, in 1980, the total market for advanced ceramic products amounted to about $600 million, of which electronic components accounted for about 90 percent.

But, although electronic components currently predominate the advanced ceramics market, many of the most interesting research and development activities in ceramics are directed at trying to expand the usage of these materials in structural products. A few of the many things currently under investigation for potential ceramic usage include gas turbines, diesel and automobile engines and parts (including turbochargers), batteries, cutting tools, heat exchangers, and numerous pieces of military and aerospace equipment. Much of this research indicates that ceramics will be combined with other materials to overcome the brittleness problem. In total, the

Department of Commerce sees a tenfold growth in domestic ceramics consumption between 1980 and 2000, when the market is forecast to approach $6 billion.

COMPOSITES

Composites are made up of two or more materials that maintain their separate identities while simultaneously exhibiting improved properties. A composite material generally consists of a matrix material in which any of a variety of fibrous materials are embedded. Common matrix materials include epoxy, various polyesters, carbon, and aluminum; glass, graphite, kevlar, and boron fibers are often used as reinforcing agents.

Composite materials first became significant during World War II in situations where high strength and light weight were required. During the 1960's and 1970's, when high-stiffness fibers were developed, composites expanded into numerous commercial applications, including electrical machinery, appliances, sporting equipment, and automobiles. The current domestic market for advanced composite materials is estimated to exceed 100 million pounds.

Recently developed engineering and processing techniques are allowing designers to take even fuller advantage of the unique properties of advanced composite materials. Owing to such favorable characteristics as light weight, high tensile strength, and improved corrosion and fatigue resistance, advanced composites are being more widely used, particularly at the expense of specialty metal alloys, in the aerospace and aircraft industries.

The key problem limiting even wider use of these new materials is their cost, which is approximately $20 per pound for the more widely used advanced composites. New uses and declining costs are expected to contribute to a compound growth rate ranging between 10 and 15 percent through 2000.

METALS

Finally, we come to metals. Collectively and as a separate class of materials, metals seem to be facing more intermaterial competition as a result of advancing technology. Much of that same basic technology, when it is applied to metallurgical science, can open new horizons that are just as dramatic as those currently opening in the other major materials groups. For example, new microanalytical devices and methods make it possible to study solids at the atomic level. An improved ability to manipulate and control the composition of and, therefore, the properties of alloys will result. Doesn't that sound like what is happening in polymer blends today? Indeed, some experts have compared rapid solidification technology, which enables the structure, makeup, and stability of metals and alloys to be controlled much more rigorously, to the discovery of polymers.

In addition to placing greater reliance on more advanced materials, domestic materials firms can also use the new technology by incorporating various technological advances into their products and thus increasing their value. Hence, many firms are now attempting to penetrate the more specialized and highly profitable market niches that would help further differentiate them from the commodity producers. Such an approach requires a closer relationship between producers and the ultimate market. Several aluminum, chemical, and plastics producers, in particular, are now doing just that.

PROCESS

So far, I have attempted to describe how advancing technology (a byproduct of the information economy) is creating new opportunities for metals companies in the form of a broad array of new knowledge-intensive materials and goods. But, up to this point, I have focused only on the demand side of the materials picture, on product rather than processes. We should recognize that our consumption of tonnage commodity metals such as steel and copper, though perhaps declining somewhat, will nevertheless remain large. And, if we are to maintain any significant domestic capability to produce such important metals over the long run, U.S. producers will have to overcome the fundamental competitive disadvantages from which they suffer, particularly labor costs. Hence, a technological strategy for commodity metals must also focus on the "process side," on applying our high-tech advantage toward the development of highly automated, advanced extractive and processing technologies that will reduce labor expenses and other cost components of the traditional supply equation. Nothing less than revolutionary mining and mineral processing systems are needed. For example, now may well be the time to begin seeking in earnest a revolutionary breakthrough in biotechnology that would enable manmade organisms to selectively leach valuable minerals from surrounding host rock.

New sensors are needed that are both sufficiently sophisticated to discriminate among a wide range of heterogeneous feed materials and robust enough to function reliably in extremely hostile smelter environments. Such sensors could provide data needed to continuously monitor major operating parameters in the smelter and thus would support the development and adoption of robotics and, ultimately, of the automated smelter—the metals' industry version of a petroleum refinery. Sensors currently perform analogous functions under less demanding conditions in other industries, and their development and application in the metals business would certainly represent a strategic breakthrough.

As an extension of this same idea, mineral producers need to apply advanced information technology much more widely throughout their mines and smelters. Such systems would provide the type of comprehensive and accurate data on the firm's performance needed to improve the quality of its goods and services while simultaneously reducing labor and other costs.

I have presented just a few examples of how innovative technology might enable the mineral industries to compete more effectively in today's world market. There are, of course, many other innovations that could further support this same purpose. The point is that, in the mineral industries, perhaps as never before, an innovative approach is needed. Nothing less than their very survival may be at stake.

HOW?

So how does a traditional, old-line mineral and metals company convert itself into an innovative, more aggressively market oriented, high-tech materials performer? Of course, there are no easy answers to such a question. Indeed, most metals firms, largely because they are in such difficult financial straits, are severely limited in the rate and extent to which they will be able to avail themselves of the new opportunities emerging in materials. Still, options do exist, and they can be divided into three broad categories: (1) the research, development, and capital expenditure approach, (2) the acquisition (or external) approach, and (3) the joint venture (or combination) approach. To demonstrate how a metals firm might combine these methods into a unified readjustment strategy, I am going to use as an example Alcoa, a commodity metals company that is currently undergoing an industrial metamorphosis.

THE ALCOA EXAMPLE

As the largest aluminum company in the United States, Alcoa has adopted a new business strategy designed to help ensure its continued survival as an autonomous corporation. The rationale behind Alcoa's new strategy was concisely described by the firm's vice president for corporate planning recently when he said, "In a postindustrial society, materials intensity is not where it's at. A business built on pounds is not going to get it in materials as such. The trick is added value and sophistication."

Hence, in phase one of its strategy, Alcoa is moving the firm gradually away from commodity-type markets and toward more highly engineered products having a higher added value. Simultaneously, it is increasing its investment in selected areas of its aluminum core business to protect against further erosion of its market share by foreign competitors and alternative materials.

Alcoa has adopted an incremental approach in moving away from commodity materials and has ruled out a major dramatic plunge into an unrelated business such as oil or real estate. As part of its approach, the firm is undertaking small joint ventures and selected acquisitions in several new product areas. For example, it has recently formed separate joint ventures with Nippon Electric Co. of Japan to produce satellite receiving systems; with Fujikura, Ltd., also of Japan, to produce optical fiber cables; and with another firm to produce specialty aluminia chemicals.

The second phase of Alcoa's strategy entails adding more value to the materials that it produces by expanding its downstream processing capacity. For example, it is beginning to produce highly engineered forgings, extrusions, and castings of aluminum and other metals and is now manufacturing finished aluminum computer memory discs at 50 times the value of the unfinished aluminum material that it formerly sold for this purpose.

A dramatically increased budget for Alcoa's research and development laboratories constitutes the third major phase of its redeployment strategy. Of special interest is the fact that 25 percent of the company's research budget is allocated to ceramics and polymers, materials in which the company is not presently a significant commercial factor but which it feels have high potential for future growth opportunities.

Simultaneously, Alcoa is strengthening its basic aluminum business to protect against further market encroachment by foreign and alternative materials producers. To protect its huge beverage can market from plastics, it is investing $700 million in modernizing four can sheet plants, and it is increasing its production of ultra-light aluminum lithium alloys to compete with composites in the aerospace market.

Finally, Alcoa will be deemphasizing ingot sales as it continues to phase out its high-cost domestic smelting operations. As replacements, Alcoa is bringing onstream large new smelters in countries where power costs are lower, such as Brazil and Australia. Alcoa's domestic fabrication plants are already receiving ingots from the Brazilian smelter, and it is anticipated that the Australian smelter will soon be an additional source of ingots for these plants. Alcoa has indicated that it will be buying more primary aluminum ingot on the open market.

CONSTRAINTS

Notwithstanding Alcoa's enterprising attempt to transform itself from a commodity metals company into a high-tech materials and manufactured goods firm, the typical minerals and metals producer faces numerous constraints that would limit any attempt to follow in Alcoa's footsteps.

In the first place, financial limitations are severe. Many metals companies have been sapped of their financial strength over the past few years; prices have been depressed, assets have been sold or written down, and debt and red ink have risen. As a result, both the credit and cash with which to redeploy are in short supply. Additionally, in today's market, it is difficult to sell off mineral-related assets and use the resulting proceeds for a redeployment-directed acquisition or joint venture. Finally, of course, stringent cost cutting has vastly reduced research and development at most mineral and metals companies and has thus virtually eliminated the internal development option.

Professional skills are also a limitation. Given the advances currently taking place in science, commodity metals companies desiring to survive by shifting into advanced materials and higher value-added goods require personnel trained in a whole new range of professional disciplines, beyond the traditional earth- and mineral-science triumvirate of geology, mining engineering, and metallurgy.

As a related matter, there are also cultural or organizational constraints. Commodity companies require managers skilled at investing major sums of capital into large production-oriented systems, typically within relatively rigid and formal hierarchial organizations. On the other hand, the culture of a successful producer of more specialized materials and goods typically is organized to produce and market a wider range of items that sell at higher prices and in smaller lot sizes. These types of firms typically are oriented more toward marketing than production and have a flatter, more decentralized organizational structure that can more quickly identify and respond to new opportunities as they arise.

Finally, those mineral and metals firms successful at maneuvering through these obstacles are likely to find that competition in the technology-intensive materials is very strong. The new competitors, however, will not be developing countries; rather, they will be major chemical companies such as Dupont, Allied, and Hercules that are already entrenched in the field and manufacturing firms such as General Electric, IBM, Westinghouse, and AT&T that are backward integrating.

WHAT COULD HAPPEN

As a result of such constraints, only the largest and strongest mining and metals companies (firms like Alcoa, Reynolds, Phelps Dodge, or Amax) appear to have the resources needed to fully exploit the dynamic new opportunities that are emerging in materials. Other mineral companies stand ready to enter into technology-intensive growth areas.

Indeed, retreat from commodity metals already seems to be surfacing. As their annual reports and other public announcements indicate, these companies are moving into areas such as precious metals, coal and other energy minerals, and nonmetallic mineral ventures. They also appear more willing to sell their services as consultants in exploration, design engineering, mine management, and minerals marketing to foreign producers. In other words, they generally appear to be moving into areas where their present skills can be more readily adapted, areas that would seem to offer less growth potential but that do not appear to be as alien or risky, either.

Thus, what seems to be on the horizon is a much more heterogeneous mineral and materials industry in the United States. Some firms could indeed evolve into full-fledged materials companies, whereas others may gradually transform themselves into natural resource companies interested in a broad range of metallic, nonmetallic, energy, and other activities. The growing role of foreign firms as partners and owners in domestic mineral operations will add yet another dimension to the once highly ordered structure of the minerals industry in the United States. And, in line with the technological resurgence now occurring, several mines and smelters in this country could well be renovated and converted into highly efficient, state-of-the-art, world-class competitors and thus help to keep U.S. self-sufficiency reasonably high in tonnage metals. Given the changes that are occurring in markets, technology, and foreign competition, however, it seems doubtful that any firm will be able to survive as a pure-play commodity metals producer in the United States.

THE TECHNOLOGICAL SOCIETY AND ENVIRONMENTAL VALUES

By David E. Gushee
Congressional Research Service, Library of Congress

INTRODUCTION

So far today, you have heard about how important minerals are to our modern technological society, how important minerals assessments are to minerals, and how important national policies are to both minerals and minerals assessments.

The speaker just before me introduced nonmineral factors into the picture. He talked about some of the economic impacts of minerals exploitation. It is my job to go a bit further in this direction, to talk about how environmental values can apparently come to mean more to a society than minerals do, even when minerals are, in fact, one of the essential elements of our technological society.

Just as the demand for minerals can be expected to increase over time, so also can the demand for environmental values be expected to increase. And, since neither minerals nor many environmental values are renewable, it looks to me like more of the decisions affecting minerals development will be brought into the public sector when they conflict with environmental values. When one adds in considerations of diplomacy and security, both of which also can be expected to increase in frequency and complexity, minerals assessors can expect to be talking to a lot of cultural strangers in the future. Policymakers will be struggling to understand the meaning of mineral assessments in the context of a host of nonmineral concerns.

You are all aware of the growth of and the power wielded by the environmental movement. Its record of achievement over the past quarter century is truly impressive. Would that all of us could lobby as effectively as it has during this period.

A record that good cannot all be because of good lobbying. There must also be something fundamentally valid about the environmental message. Lynton Caldwell, one of the quiet mainsprings of the environmental movement, has said it quite well (Caldwell, 1984, p. 18):

> Humanity appears to be in a race between the destructive consequences of its impact upon the environment and the recognition of the necessity of remedial action....this race..., although it may be called a race against time, is more truly understood as a race between man's inherent propensity to act upon his environment and his capacity to learn and foresee. The history of...environmental policy may be seen as a demonstration both of human capacity for social learning and of the enlargement of human intelligence in response to challenges posed by the insufficiently informed and disciplined exercise of that same intelligence. The race is between two aspects of the human character.

We tend to act first and to clean up later, if we clean up at all. If the environmental movement means anything culturally, it means that we as a society are formally recognizing more cases where we need to think about cleaning up before we begin the process of doing whatever it is our material or psychological needs demand.

The process of thinking about things before we do them operates at many levels. There is the national policy level established by Congress. There is administration policy, then department policy, agency policy, program policy, office policy, and (at the bottom of the totem pole in this analogy) personal policy. State and local governments have analogous levels. In the private sector, there are corporate policies, division policies, and so on, down to the project and individual levels. And there are equivalent policy levels in the other sectors of society--consumer, labor, environmental, and the like.

This process of thinking about things before we do them is to a large extent "planning." At whatever level we operate, we take into account whatever we think we ought to, and we exclude some things that we ought to include. I imagine that each of us excludes some things that ought to be included, basically because we do not recognize that they ought to be. And, I imagine, we do take into account some things that we have to, even though we may not think that we should have to. But, then, we as individuals learn as we go, just as societies do.

Planning, however, is not linear; neither an individual nor an institution does it in a vacuum. Instead, we take a shot at it, pass it by others who care, and wait for the feedback. The final course of action is usually a lot different from the initial proposals, as a result of these back-and-forth movements.

In public policy formulation, the back-and-forth process is a lot messier than it is in a corporation or an agency. Picture, if you will, a tug of war with a rope. In the middle is a big knot, which represents the decision to be made. On the ground under the rope and somewhere near the knot is a line. When the knot crosses over the line onto one side and stays there, the decision has been made.

At one end of this particular rope are people representing all the forces working in favor of an initiative (say, minerals development in general) plus the forces working in favor of development of the particular deposit or set of deposits under consideration. At the other end of the rope are people represent ing all the forces working against minerals development in general and the particular development under consideration. These people or sets of forces are engaged in this tug of war against one another.

To make the picture somewhat more realistic, visualize also these people milling about, so that their efforts are not highly organized, as they would be if they were coordinated teams or members of the same organization. Add in some spectators representing general social trends, who jump in from time to time and pull or push (or perhaps even lean) on the rope in highly disorganized ways. From time to time, one of these spectators moves up to the rope, grabs hold, and starts pulling, a move that represents a social policy decision adding another factor explicitly to the equation.

Let us keep this general picture in mind as we review the three major environmental considerations that we have been told by Congress to include in our thinking and try to figure out on which side of the knot they will be.

First are the natural attributes of the land. Some parts of nature are deemed by society in general to have natural attributes that should be preserved, regardless of what other values the mix of resources might have. This judgment is relative--when it was made, the natural undisturbed value was considered to be greater than the values that would have been derived from disturbing the area.

Included in this set of factors are both inanimate and animate elements. Among the inanimate elements are vistas, unspoiled rivers, and particular geologic structures and formations. Among the animate elements are habitat criticality (special breeding grounds, for example), species diversity, wildlife preservation, environmental fragility, special stands of long-lived trees, and a number of other ecological values.

Protection of natural attributes and development of mineral potentials tend to be mutually exclusive. The inanimate factors are always lined up foursquare against development, since they tend to be unique and irreplaceable. The people who promote these factors are known as "preservationists." The animate factors are usually, but not always, on the "anti" side. Some of these values are retrievable or substitutable under the right circumstances, while others, once they are gone, are gone forever. People working in these areas can be either preservationists or "conservationists."

The factors involved in environmental quality, the second area to be considered, include air and water quality, visibility, contributions to water supply and CO_2 absorption, and climatic effects. Aside from the extent to which preparing an environmental impact statement causes them to be explicitly considered, most of these factors are implicit in land use decisions made today. There are no statutory or procedural requirements to consider the impact of a proposal on emission of acid rain precursors or on CO_2 buildup or ozone depletion, for example, although, in some parts of the environmental community, people think that there ought to be. In tune with our analogy, these factors represent spectators occasionally taking part in the tugs of war.

Although these factors are usually lined up for environmental values and against development, the two are not necessarily mutually exclusive. It is frequently possible to have both, provided that people on both sides are willing to work toward mutually acceptable outcomes. We find in this arena activists from both the preservationist and the conservationist camps.

But, in this tug of war, mining is at odds with more than natural attributes and environmental quality. A third major consideration is nonmining economic uses of the environment's assets. Such uses might include recreation and tourism, agriculture, grazing, dams, and timber harvesting. One might even put general economic development in this category, since it occurs frequently as a result of some environmental asset such as the presence of a river or a natural passageway through mountains. Some of these forces may already be tugging on the rope when the mining interest comes along; others join in after the fact, perhaps even as a result of the mining activities.

Most of these factors compete with mining development most of the time. The difference is that, even though it might not be possible to have both, the protagonists speak the same language and find that the rules of the game come naturally to them. Protecting the environmental status quo is seldom a governing consideration.

CONFLICTING DEMANDS

Various interest groups are continually seeking to achieve their objectives. This statement is as true of those supporting ecological values as it is of those seeking to develop minerals as economic inputs. There has to be a process by which conflicting interests can be brought into the same arena and some sort of accommodation reached. To resolve the differences between economic and environmental values, the process must include some prior judgments about particular areas, the environmental impact statement process, various permitting requirements, and judicial appeal. I am sure that I have left out a few others.

The point that I want to make is that, as the imperative to develop mineral deposits grows with increasing population pressure and economic development, so also does the imperative to protect environmental values and assets.

In minerals development, for example, the imperative is a demand for a mineral, that demand being some mix of society's need for the mineral as a function of price and other factors plus the supply curves for specific deposits and for the resource as a collective whole. The richer a deposit and the greater the consumption of the metal in that deposit, the greater the driving force to develop that deposit.

But the other forces have their own supply and demand curves. One ordinarily does not think of demand curves for wilderness and rhinoceroses, for furbish louse warts, snail darters, and rattlesnakes, or for migratory bird flyways, but, in their own peculiar way, they do exist. The independent variable is not market price, though; instead, it is some distilled form of population pressure, social awareness, and societal economic well-being. This societal sense that something valuable is becoming very scarce or is in danger of being lost forever is the counterpoint to the mineral commodity price. The rarer the resource and the greater the recognition of its intrinisic or ecological value, the greater the driving force to protect that resource. The resulting demand curves look quite conventional, despite the fact that the driving variable is different. Similarly, the supply curves look to me like the depletion curves used for mineral deposits or oil wells, which show declining quality or increasing cost over time.

When "environmental goods," such as a flow of water, are used to support the economy, the supply and demand curves behave normally. But, since the supply and demand curves for the noneconomic benefits of environmental goods are based not on price but on societal value, public policy intervention is the only way to ensure that the nonmarket values get a fair hearing.

Since the market-driven power of mining development has so often overwhelmed the more diffuse strengths of environmental goods, Congress has, particularly over the past 25 years, written additional ground rules requiring inclusion of these noneconomic values in the decisionmaking processes. Legislation on wilderness, wild and scenic rivers, and critical habitats and the study programs on roadless areas fall into this category. These provisions have taken large chunks of land out of the resource base, so far as minerals are concerned. Environmental impact assessments have forced consideration of environmental values for those lands not so removed but still under Federal jurisdiction. States and local jurisdictions have added their own versions to affect the areas under their control. Various permitting requirements complete the picture.

It is very difficult these days to develop anything without having a tug of war with social policy, because so many environmental goods have formalized their demand functions. But there are other environmental goods that have not succeeded in getting their demand functions into the social policy decisionmaking process. I refer here to acid rain, the resolution of which may well significantly increase mineral-processing costs, ozone depletion, the relation between CO_2 and forestation, and a whole range of land disposal requirements.

So, as our technological society's need for metals increases, minerals supply curves tell us that we can get more if we are willing to pay more. Those curves are not yet capable of incorporating the effects of domestic social policy decisions that take some pieces of the resource base out of the picture. That capability would be an interesting attribute. The supply curve would look one way if we could go anywhere in the United States but quite another way if we eliminated areas removed from consideration because of wildernesses or critical habitat or some other environmental factor.

This sort of bifurcated approach is already used to some extent for issues of domestic versus nondomestic production. There, a value conflict occurs in which a set of noneconomic policy issues (diplomacy or security, perhaps) are weighted against economic ones.

In dealing with environmental factors, the tradeoffs are similar, but they are in arenas where we have had less experience. Further, environmental demand curves are not so well developed, and the need to develop more of them is increasing.

In sum, the demand for environmental values can only be met by public policy intervention. That demand usually works against minerals development and often even works against minerals assessment. Some interests are concerned lest the process of assessment generate an imperative for development that would cause the loss or impairment of the environmental value.

Further, the scope of public policy intervention grows as society learns about more things that matter to it. Life gets tougher as we learn. But, at the same time, societies learn how to cope with complexities over time as they go through the processes of dealing with them. So, life also gets easier as we learn. And that observation brings us back to where we began, to Lynton Caldwell's observation that these problems and opportunities are inherent in the nature of man.

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MINERAL DEVELOPMENT AND PUBLIC POLICY: A CANADIAN CORPORATE PERSPECTIVE

By O. E. Owens
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INTRODUCTION

This paper addresses three issues from the perspective of Cominco, Ltd., a major Canadian mining company operating in Canada, the United States, Australia, Spain, and Greenland: (1) the influence of "Federal stewardship" on resource development, (2) prime elements that encourage or discourage resource development, and (3) public land assessment programs that help resource development.

As these issues are examined, reference will be made to three northern lead-zinc projects developed by Cominco over the past 21 years. Pine Point was commissioned in 1964 as a multiple open-pit operation in what was then an extremely remote location in northern Canada. The Greenex Black Angel mine, brought into production in 1973, on the western coast of Greenland, lies within Danish jurisdiction and is a unique cable-car-serviced underground operation in permafrost. Polaris on Little Cornwallis Island, the world's northernmost metal-mining operation, commenced production in 1981 about 60 miles from the magnetic pole. Both Polaris and Greenex sited at tidewater but can ship only during the ice-free summer months. Cominco's most recent development project is the Red Dog deposit in the northwestern corner of Alaska. It is larger than the three deposits just mentioned but at present is only at the final permitting stage.

FEDERAL STEWARDSHIP

Until recently, Federal stewardship in North America has been clearly supportive of resource development. Resource development provided the abundant new wealth necessary to found and sustain a healthy economy for an expanding society. It brought new value out of the ground, produced wages, taxes, and wealth for society, and also established new communities, plus the incentive for many of Canada's initial transportation links.

In today's complex economy, when 70 percent of the population derives its income from the service sector, it has become increasingly difficult for the general public to see and appreciate the fundamental importance of mineral development. People engaged in activities further along in the economic chain seem unable to recognize their continuing need for both the new domestic capital and the new metals thus created.

A common misconception is that the value of a mineral deposit vanishes once its reserves are gone. People tend to see only an empty hole in the ground and to forget that its original value and most of the metal remain as permanent additions to national wealth. Mining's contribution survives in the physical form of metallic products—automobiles, airplanes, copper wire, steel buildings and bridges, and so on. It also survives in the form of money in circulation from wages and dividends paid. Resource development will continue to be one of the primary foundations upon which socioeconomic structures are based.

A mineral deposit, in practical terms, simply does not exist until it has discovered and developed. This concept can be difficult to grasp, however, since many people harbor the impression that a nation's unexploited mineral wealth can be quantified and developed whenever necessary. It is not that easy, as explorationists know when they go through long, dry periods without any tangible success, and it requires the maintenance of a viable mineral and exploration industry if there is to be a domestic capability for ore discovery at all.

In the mid-1970's, the Club of Rome cautioned that society should not develop and use its scarce resources too quickly. What the club failed to recognize, however, is that known mineral resources have historically appeared inadequate to meet projected long-term demand, yet they have always remained more than adequate for current consumption. Proof of this assertion lies in the fact that real metal prices have traditionally fallen, not risen, over time. Fortunately for the consumer, the long-term price trend shows no sign of changing. Moreover, North America's beleaguered mines are constantly challenged by fresh discoveries being made in other countries.

It has been Cominco's experience that few serious problems have arisen in accommodating realistic environment al requirements within responsive new mine development programs. On the other hand, the mining industry has, in the past, done things that were less than environmentally responsible, partly through ignorance and lack of planning but largely through simple conformance with the norms of the day.

However, at least for new mining developments, those days are past. Industry today understands environmental needs, and engineers undertaking the design of new installations do so in the current climate of environmental awareness.

In summary, there is a fundamental need to maintain a supportive Federal stewardship policy toward resource development. This vital source of new wealth should not fall by default to foreign interests, upon whom we are becoming increasingly dependent for both metals and mining expertise, while our internal supply structure withers and dies, affecting our balance of payments negatively. A supportive Federal policy need not be in conflict with an equally responsible policy toward environmental protection.

PRIME ELEMENTS AFFECTING RESOURCE DEVELOPMENT

The second issue that this paper was asked to address is prime elements that encourage or discourage resource development and how they have affected Cominco projects.

Positive elements include:

oBroadest possible access for exploration.
oClear, stable conditions of mineral rights tenure.
oStraightforward and practical permitting and regulatory procedures.
oStable and equitable taxation treatment for both mining corporations and their employees.

The mining industry seeks the opportunity to explore for mineral deposits wherever, within reason, they may occur. It also seeks assurances of a fair and stable framework of mineral land tenure, operating regulations and taxation conditions within which discoveries may be responsibly and effectively brought to fruition.

In recent years, some Canadian and U.S. policies have been policies and actions not only have failed to encourage mineral development but have also actively hindered it by limiting exploration access. Most alarming are the substantial land alienations already in place and the extent of additional alienations under consideration. Orebodies are few, far between, and difficult to find at the best of times. Only a miniscule portion, if any, of any vast tract of geologically favorably ground will ever host viable mineral reserves. Without exploration access to most of that tract, the exploration becomes as futile an exercise as fishing in a puddle.

In Canada, approximately 7.5 percent of the Yukon and Northwest Territories has been set aside for national parks, wilderness reserves, bird sanctuaries, game reserves, caribou calving grounds, and archaeological sites and are thus closed to mineral exploration or severely restricted. Many more regions are being considered for these same purposes, in addition to which are the sites proposed for inclusion in the International Biological Program, which would double the land area presently under curtailment. And, in Canada, there is still the unresolved issue of native lands.

In Alaska, the situation is even more extreme. One author calculated that 68 percent of the land considered to be within high-potential mineral belts has already been formally closed to exploration and mining.

Stepping back to gain some perspective on the question of mineral-land requirements, one is immediately struck by how little land is actually involved in mineral production. Estimates suggest that only one-seventyfifth of one percent of Canada's surface area has been touched by mining. In the Province of Ontario, which probably hosts the country's highest level of mining activity, the area devoted to mining is less than that devoted to just the interchanges along one of its major highways.

Such land as mining occupies is frequently being returned in condition suitable for alternative use. Mining occupation may even be of relatively short duration. Paradoxically, it is this environmental advantage that mining has over other industries that draws criticism from socioeconomists. They complain that individual mining operations and directly related facilities are not permanent enough.

Since no endeavor, regardless of how necessary, can please every single-minded interest group, enlightened Federal policy and stewardship are needed to set priorities. Responsible selection for grounds for national parks is a key item. Government has a fundamental obligation to evaluate the mineral potential of any area where restricted exploration access is proposed in the same way that it would evaluate the wildlife or other resources to be protected within the area. Adequate money and time must, of course, be allocated, but, most importantly, the evaluation must be performed by competent geologists working from first-hand field observations, not by mineral economists working from some arbitrary set of criteria.

This evaluation should be performed in two phases, the first being a preliminary assessment of the general region under consideration and the second occurring after specific boundaries have been proposed. This second phase affords an opportunity to make critical adjustments based on more detailed work conducted within boundary areas. Once a withdrawal has been established, however, why should its boundaries be fixed for all time, if knowledgeable, concerned people think that an exchange of territory would benefit all? Although there is tremendous pressure from environmentalists to prevent any changes, can the total population and total need allow such an absolute to prevail? Land set-asides should contain a clause providing for boundary changes in the case of clear desirability.

It should go without saying that, in addition to having the right to explore, one must be reasonably assured of the exclusive right to responsibly develop and operate any mineral deposit that he may be fortunate or skillful enough to find. Security of title is a must throughout the entire exploration and development sequence.

Over the years, revisions to the original regulations governing operations at Pine Point have been adopted to cover valid concerns as they arose. The same scenario, repeated at other Cominco operations, demonstrates that it is not necessary to try to accommodate every hypothetical eventuality when an initial permit is formulated.

Among the most frustrating experiences connected with getting a project off the ground is the time wasted while a company and various involved agencies use the adversarial permitting process to negotiate differences. Hearings can pit one protagonist against a series of antagonists instead of providing a forum where sides can discover and work to accommodate each other's concerns and priorities. The process ought to be modified in some way to become more of a discussion and bargaining process between the various groups concerned.

In those cases where more than one government body is involved in considering some aspect of a new venture, it is important that they get together early in the permitting process to determine their overall position and nominate one key coordinating agency. Overlapping and (or) conflicting regulatory procedures could thus be minimized, along with the obvious potential for project delay.

It may be helpful to review and contrast Cominco's experiences at Polaris and Red Dog. At Polaris, we first obtained our board's approval for a production program and then set out to secure the necessary permits. At Red Dog, because of the uncertainty of what will be permissible, we must go the other way around. To date, we are not yet in a position to either fully describe the project or estimate its final cost with sufficient accuracy to request our board's approval.

In both cases, we dealt primarily with one principal Federal agency in Canada (the Department of Indian Affairs and Northern Development) and one in the United States (the Environmental Protection Agency). In Alaska, we are also dealing with three other Federal agencies and a number of State bodies. In the Territories, it was less complicated, in that we had no equivalent to State agencies and thus were left to deal primarily with the Federal government.

Although there are innumerable specific differences between the two projects, two were significant. One is a matter of philosophy. At Polaris, the development was presumed beneficial, and, since both Government and company representatives could visualize acceptable production facilities, we were able to complete the permitting process during the 2-year design and construction period. The second difference appears to be that regulators in Canada have greater discretionary powers, whereas their colleagues in the United States appear to be more restricted by legislation and regulations that may not be logical when applied to site-specific realities.

In Alaska, 3 years of time, money, and staff commitment have been spent just working our way through the initial Red Dog Environmental Impact Study procedure. Design has begun, and we are only now seeking the necessary construction and operating permits. At last count, it appears that we will need about 20 major permits from various agencies, plus a host of minor permits and approvals. To give you an idea of what we are up against, I understand that each borrow pit and each stream crossing required along the 57-mile road linking the mine site to the port will need separate approval.

The bottom line is that Red Dog expenditures now stand at about $30 million, and we still have no assurance of approval. Can industry really afford such expenditures and uncertainty on a regular basis?

Extra financial risks or delays occasioned by the permitting and approval process can have an often overlooked but very real danger. As project momentum slows, corporate enthusiasm begins to wane. This enthusiasm, triggered by the initial discovery, is the driving force behind all new development projects. It is tough to generate and easily lost in the face of other corporate needs.

Our experience at both Polaris and Red Dog stands in stark contrast with what we recently encountered in Nevada, where last year we commissioned our Buckhorn heap leach gold mining operation. There, the entire process was essentially wrapped up in 6 months. Approvals were facilitated by responsible mine development plans, but the efficiency was probably in large part due the fact that mine development programs are routine business in that State. Similarly, in Spain and Australia, widespread experience with mining facilitated orderly progress of development programs. In Alaska, we find ourselves pioneering each step of the way, with representatives on both sides wishing that they had some kind of precedent to help them through the regulatory maze. The experience gained in active mining States should be able to help the process along in such new areas.

I dislike closing this section on a negative note, because we are making progress with Red Dog and have had a lot of help from understanding regulatory people. But I believe that there is room to improve the process, and it is appropriate at this conference to point out possible new approaches.

Taxation policy is perhaps the largest cost over which industry has absolutely no control Tax burdens directly affect the international competitiveness of a nation's existing operations and further influence the allocation of exploration efforts. The entire exploration-mine development sequence is planned and based on cost of production. Unstable and (or) inequitable taxation treatment, particularly royalty-type burdens not based on profit, is the prime discouraging feature. It clearly affects the selection of exploration sites as well as the deposit characteristics deemed necessary for economic viability.

As an example, the Polaris and Greenex ore deposits became available for production at about the same time. During this period, however, the Canadian Government chose to abandon an incentive package that included a 3-year tax holiday, whereas Denmark, even after discussions with the Canadian Government, arranged a tax holiday to allow recoupment of capital before taxes or royalties began for Greenex. Also, there were personal tax incentives in Greenland to encourage people to work in that extreme northern location. It is thus not too surprising that Greenex entered production 6 years ahead of Polaris.

Other elements that encourage or discourage resource development touch again on the stewardship aspect and some high-profile Federal objectives that invariably place resource development in an awkward position and commonly lead to impasse and delay. Examples include:

- Policies fostering domestic processing of raw materials that may produce pressure to build otherwise unjustified downstream processing.
- Use of "national flag shipping" for transport of products.
- "Local indigenous people first" employment policies. (Although Cominco fully embraces this concept, our principal concern is with setting fixed target quotas that may prove impossible to achieve.
- Environmental policies and regulations that attempt to provide for every conceivable concern without allowing room to adapt to the conditions actually present in an area.

Another aspect that still clouds the issue of resource development in northern Canada is the native lands or land claims question and the natives' general preference to see such matters settled before any new development is undertaken. Industry's inability to promote the resolution of such claims or even to speed the pace of discussion is obvious and simply means that industry must look elsewhere.

A major assistance that governments can provide to resource development is the building of roads to ore deposits in remote locations. These roads can also be justified as permanent avenues of access to new regions. Alaskan legislation is in place to support road and dock construction for Red Dog and that area of Alaska. The Governments of Ontario and Quebec regularly provide roads to new mines. In the 1960's, the Canadian Federal Government had a Road to Resources Program that built into the Northwest Territories in 1964, to serve the Pine Point mine in particular. Production commenced immediately, and the railway has been profitable for the Government as well as critical for Pine Point development.

PUBLIC LAND ASSESSMENT PROGRAMS

The third and final issue that this paper will address is public land assessment programs and how they can serve resource development.

Long experience in a host of developed and developing countries has demonstrated that basic topographic and geologic mapping is the most effective technical assistance that can be provided by government expenditure. Detailed target identification and deposit definition work, on the other hand, is best performed by industry.

Industry will remain largely dependent on high-caliber regional geologic mapping and correlation programs normally performed by government. Ongoing programs to complete and update regional mapping are vital to the continued success of the resource sector. I was surprised to learn that our geologists think that there is more comprehensive and complete geologic mapping available in Canada than there is in the United States, yet I believe there is a need for increased and updated regional mapping in Canada.

Other important activities are regional geophysical and geochemical surveys, satellite imagery data, aerial photograph libraries, and land set-aside studies. In more remote areas, programs such as the Alaska Mineral Resource Appraisal Program and the more general National Uranium Resource geochemical study are particularly helpful. Such government programs also promote a healthy interchange between field workers in government and industry.

Work by the Geological Survey of Canada (GSC) played a significant role in the Polaris discovery. Government mapping led junior petroleum exploration company geologists to the area, and lead-zinc mineralization was located. Cominco optioned the property in 1963, but initial work found only more showings of limited potential. Subsequent regional GSC mapping identified an unconformity within the region of interest. Cominco's thinking changed, and we carried out new geophysical work and drilled an anomaly located near the original showing. The first hole clicked, and, by late 1973, an ore deposit was outlined.

In a similar vein, U.S. Geological Survey mapping played an important part at Red Dog. Irving Tailleur's mapping in the late 1960's located mineralization in the area and later U.S. Bureau of Mines studies preceding land set-asides drew new attention to the location. Recognition of certain geologic characteristics associated with important orebodies led to Cominco American Incorporated's major exploration effort.

CONCLUSIONS

Serious as land alienations and permitting difficulties are, I see them as only symptoms of a root problem. Their impact can be lessened by fighting them each time that they appear, but we will not be close to a solution until the public discovers the extent to which its well-being is being compromised and the well-being of future generations further threatened by the often "dead-hand" approach toward resource development.

Over the past few decades, our environmentalist colleagues have performed a valuable service in warning us about the critical need to protect the initial links upon which our ecosystem depends. Their message is valid. Unfortunately, however, few seem to realize that it is also critical to protect the econosystem that supports us all.

The importance of a viable domestic mineral industry must be understood. Resource organizations will continue to speak out, but the numbers of people and funding involved today are markedly reduced by the economies necessary to the survival of industry in today's depressed state. Furthermore, industry's words are often suspect in the eyes of the environmentalists, who draw support from an only partially informed public.

The only solution is implementation of a responsible, supportive Federal stewardship initiative, complemented by a sustained program of public education. The statesmanship required for such initiative is a tall order, but we have already seen elements of it surface to work wonders at Pine Point, Greenex, and Polaris and, most recently, in support of the development of Alaskan transportation facilities for Red Dog.

It is the Government's role to achieve a balance between environmental protection and resource development that will address national economic and strategic needs as well as environmental interests. The mineral industry will want to cooperate in this endeavor--this conference is an example--but industry is becoming preoccupied with the survival of its existing operations. It may not be able to undertake broad enough programs to motivate a generally disinterested public. Government is in a position to see the proper need and work accordingly.

Another theme that I would like to emphasize in closing is the important role that government has played throughout the last century in working out the field relations and producing the geologic maps that are so valuable to mineral development. The need is as great today as it ever was to complete national coverage and to update existing maps to bring them in line with today's understanding and technology.

U.S. INDUSTRY'S PERSPECTIVE ON MINERAL RESOURCE APPRAISALS

By John C. Wilson
Anaconda Minerals Company

INTRODUCTION

I would like to thank the convenors of this joint U.S.-Canadian meeting for inviting me to speak at this workshop. As an exploration geologist turned manager, I am intrigued by the similarity between the mineral resource appraisal process and the reconnaissance mineral exploration process. Although the goals of the two are different, the processes are similar and permit useful analogies. My current assignment with Anaconda is a team charged with disposing of the nonfuel mineral assets of this 110-year-old company and completing the closure and cleanup of its widespread operations. Drawing on this experience, I would like to offer a few comments on the future of the industry in this country and its role as a domestic supplier of raw materials in ordinary and extraordinary times.

The American mining community is fragmented, and it would be very presumptuous of me to speak for the whole industry. Therefore, I will talk mostly about my feelings on mineral resource appraisal. And, at this point, I would like to acknowledge intensive discussions with and insight provided by Dick Nielsen, Greg McKelvey, Lin Schmale, and George Secor in preparing this talk, although I absolve each of them of any responsibility for these remarks.

There are five main points that I would like to make.

First, the mineral resource appraisal process would gain more support from industry if it were divorced from the single issue of wilderness selection.

Second, the Conterminous United States Mineral Assessment Program (CUSMAP) is a good program that should be expanded and improved to form the cornerstone of the land use planning process. Many mining industry professionals share my enthusiasm for the data, the map presentations and deposit models, and much of the analysis.

Third, the mineral resource appraisal work done for the Bureau of Land Management (BLM) by the U.S. Geological Survey (USGS) and the U.S. Bureau of Mines has problems with project design, communication, politics, and, possibly, quality. Although these programs produce some good data and their product is a suitable precursor to modern detailed exploration, the appraisals are inadequate as a planning tool in wilderness decisions. The studies are flawed by, among other things, faulty logic, such as, "If mineral production is not economically possible from the prospects in the study area now, then no production is likely from any type of deposit in the area at any time in the future...." Explorationists who follow that line are generally unsuccessful, and most are currently among the burgeoning ranks of the geologically unemployed.

Fourth, there are two types of mining companies: older, large-capital firms that are staying alive by producing coal, gold, or industrial minerals while coping with their environmental liabilities and smaller mining firms that seek gold, take much higher financial risks, and are funded largely by non-U.S. capital. Neither group is in any condition to contribute to the massive land use planning process currently underway in the United States, and neither group could respond rapidly in an emergency.

Fifth, in the view of most exploration industry professionals, the role of the USGS is to accurately describe and record the composition and character of the Earth's crust. The USGS should be collecting and communicating data, identifying areas that are favorable for mineral deposits on a regional scale, studying the geologic settings of ore deposits, and describing deposit types that are likely to occur but not assessing economic aspects. USGS documentation of areas where ore deposits are likely is worthwhile, whereas rigorous calculation of the value of those deposits is not. However, USGS development of quantitative evaluation methods is important and appropriate, because its customers need these methods to formulate their land use plans.

HISTORY OF PUBLIC LANDS IN THE UNITED STATES AND THE MINING INDUSTRY

In 1982, I described to the American Mining Congress the history of U.S. public lands in four phases: (1) acquisition, ending in 1867 with Alaska; (2) land disposal, including the Homestead, Land Grant, and Mining Acts; (3) conservation, including retention of land in public ownership as national parks andf Forests; and (4) stewardship, featuring controlled sustained yield and Federal land management.

I told my audience that they should view the land disposal era as definitely over but that there was a question about whether we would stay in that fourth phase or move into a fifth phase of preservation and nonuse. I said that, even if our industry were in bad shape, we should increase our involvement in the land use planning process, because mineral exploration input was vital for high-quality mineral resource appraisals. Three years later, the debate continues between stewardship-multiple use and preservation.

Unfortunately, land use planning, of which mineral resource appraisal is a part, is viewed by many in mining as a thinly veiled attempt to justify previously made wilderness lock-up decisions. The problem was caused by two conflicting trends in the 1970's: the conservation-preservation trend developing from public concern over destruction of our magnificant wild areas and a second trend developing from the perception of an impending resource shortage predicted earlier by the Paley Commission and later by the Club of Rome computer projections. These perceived shortages were made more real by the oil embargo and by speculators who hoped to profit from the impending short supply. In reality the perceived shortages proved to be surpluses, in large part because of the success of exploration throughout the world during the last 35 years. However, the animosity between the preservers and the producers remains.

The precipitous economic decline produced two industrial segments: established mining companies and new small, flexible firms. In order to survive, older companies must focus on their remaining resources by selling assets, cutting costs, concentrating on coal, gold, and industrial commodities, and placing properties that produce the basic commodities on a standby or, worse, a reclamation basis. As a consequence, this Nation's ability to produce its share of world commodity requirements in ordinary and extraordinary times is rapidly eroding. Of course, this national policy issue is beyond the scope of this workshop, but any discussion of mineral resource assessment must take it into account. From the miner's long-range point of view (if he can afford to have one), mineral resource appraisals should focus on where new mines are likely to be found to replace the ones that are being exhausted. Classification of public lands as wilderness should not be the sole purpose of mineral resource appraisal.

A few companies without significant mining liabilities, are cautiously acquiring basic commodity properties in the United States, where assets can be obtained at a significant discount. A very few other large companies are looking for hitherto undiscovered resources of base-metal and industrial commodities, mostly in foreign areas. These companies shared their data bases with government agencies 5 years ago in the hope of producing more rational land use decision policies during the RARE (Roadless Area Review and Evaluation) II process. The poor health of this segment of industry and the generally poor reception that industry data received in congressional hearings make it unlikely that these sources will volunteer much new information in the future.

The new players on the American mining scene also focus on gold. These firms make decisions very quickly, have no bureaucracy at all, and are focused very closely on maximizing profits. Their environmental sensitivity remains to be demonstrated. Contributing data and ideas to land use planning is not on their agenda, either.

So, why bring up the distressing condition of the mining industry? It leads directly the question of why this Nation need mineral resource appraisals if we, as de facto national industrial policy, are quickly extinguishing the domestic metal mining industry.

INDUSTRY PERSPECTIVE ON MINERAL RESOURCE APPRAISALS

Contact with about 20 people, mostly in exploration departments, yields a fairly uniform reaction to the question, "What do you think of the Federal Government's mineral resource appraisal efforts?"

Now, I cannot say that this hot topic is on the tip of everyone's tongue, like it was before 1982. In fact, the question was greeted with stunned silence on most occasions, because it was displacing more pressing subjects such as the future of American mining, exploration ideas, and job security. Mineral resource appraisal is related to these more pressing matters, of course, but it is not relevant to most professionals with whom I spoke. A few generalizations on industry sentiment follow.

As a one-time effort, mineral resource appraisal is an impossible task. Exploration is a form of resource appraisal that has worked very well in this country. Unlike mineral resource appraisals, however, it is a discontinuous but repetitive activity that is revitalized by new concepts, new knowledge gained through drilling, new geologic mapping, or changes in mineral economics. Mineral resource appraisals prepared for the U.S. Forest Service (USFS) and the BLM, for example, contain good data on what past mining and prospecting have exposed. In this sense, the appraisals are descriptive. Description is one of several elements that mineral exploration and the appraisal process have in common. The others are the development of geologic models appropriate for the geologic environment, the completion of fieldwork to fill gaps in knowledge, the analysis of a data base in connection with models, and the prediction of the favorability of an area. Exploration integrates these elements, and some CUSMAP projects do as well, but many other appraisals do not. A national mineral inventory based on CUSMAP is a worthwhile objective, especially as part of integrated and ongoing land use planning.

I will elaborate now on some of the problems that the exploration community has with the appraisals currently underway on BLM lands. The problems fall into three groups: (1) project design, (2) communication, and (3) politics.

Project Design

The small size and odd shape of most wilderness study areas can affect the quality of appraisals. The outline of each area is determined by its suitability for wilderness and not by its geology. Thus, an area might be 10 times longer than it is wide, and the long dimension might cut across the geologic grain in some illogical way. The geometry of the area and funding restrictions force the investigator to study these small areas out of geologic context.

Another problem in project design is the scales at which the studies are made. There are too many scales, and they are too large. A scale larger than 1:125,000 is too detailed to provide an efficient definition of mineralized tracts. The work should focus on defining favorable regions for ore deposits, which commonly have dimensions of 10 to 500 mi^2. Unfortunately, this size range is the same as most study areas. Such detailed work tends to focus the analysis inside the geologic forest and also produces subdivisions that seem too small to manage for adjacent wilderness and multiple use.

A third problem in project design concerns work methods, staffing, and external constraints on interpretation. Compilation of past mineral development in these studies focuses on what has been found rather than on what might be found in and around these areas. Further, the quality of some of the work reflects little of the insight of a seasoned exploration geologist. Exploration models are seldom referred to. Review of several of these studies by a select cross section of the exploration community should lead to constructive suggestions and probably a significant improvement on some.

The human factor comes in at this point. It is difficult to be positive about the unknown, yet the geologist is asked to predict undiscovered ore deposits, to make a projection and stake his reputation on scant hard evidence. It is easier for him to be negative or neutral and adopt the "there's nothing there" attitude. Who is going to check, and when? Given the combination of de facto industrial policy and human nature, objective evaluations are and will be difficult to produce unless this conundrum is acknowledged.

Communication

A more serious problem is communication between the geologist writing the appraisal and his customers, who apparently are departmental, agency, or congressional staff formulating policy. We cannot see that appraisals have much of an impact on policy recommendation, and we are not sure that they have been read or understood. They either arrive too late, or they are in the foreign language of geology, or the conclusions are diluted to the point of incoherence. I feel that the USGS needs a liaison group to communicate its results to its customers, whether they be the USFS, BLM, or Congress, and that communication must be in the language of the customer.

The communication problem also revolves around the difference in what the customer wants versus the product that the USGS is providing. The USGS delivers qualitative rankings of mineral potential and outlines areas of contrasting potentials. The customer, however, probably wants a quantitative evaluation of those areas of contrasting potentials, so that he can compare mineral values with values assigned to other resources in the study area. Quantitative values of mineral potential can probably be calculated by using the frequency of occurrence of each deposit type in a control zone that is well explored, the grade-tonnage model for the deposit type, and the acreage of high and medium potential in the study area. The USGS should work out the method and provide the frequency-of-occurrence data. The USFS and the BLM should do the calculations and qualify the results.

A useful analogy for handling the communication problem may exist in industry. Exploration managers are responsible for translating recommendations into language that makes sense to executive management. It keeps the funds focused on geologically sensible targets, and it depoliticizes the rank and file of the exploration staff. Whether a similar system should be developed in the USGS or whether a liaison group with this responsibility is the solution is not apparent to me. But the communication problem is obvious to many.

Politics

The final problem to be discussed is political. Let me put it as bluntly as possible at the beginning. If a viable mining industry is important to this Nation, then mineral resource appraisals of potential wilderness areas, and indeed of all areas, are extremely important. However, the de facto industrial policy (the net effect of regulations and public perception) of this Nation does not seem to favor mining; therefore, mineral resource appraisals should cease.

The same de facto policy does not make it clear where the raw materials for basic industries are coming from 50-plus years downstream. Overseas? Probably, but at prices substantially above those experienced now, when the Club of Rome's predictions finally come true. But then what? Do the third and fourth generations reopen the partially worked mines that are being reclaimed now and converted to ski resorts and retirement villages, or do we initiate a crash exploration and development program in the wilderness? That solution should produce new raw materials and a hell of a mess about 20 years after the green light is given. A good lunchtime discussion in the Department of the Interior and in Congress on the nonrenewable nature of all nonfuel minerals would seem appropriate.

CONCLUSIONS AND RECOMMENDATIONS

A few concluding and summary thoughts follow.

The quality of the appraisals could be improved by using the CUSMAP approach rather than the mineral resource appraisal (MRA) approach because CUSMAP deals with future potential as well as with the past, and it is not confined by administrative land boundaries. Appraisals on areas smaller than a 15-minute quadrangle are not worthwhile.

The USGS should develop the methodology for quantitatively evaluating areas of significant mineral potential. The USFS and the BLM should use these methods to quantify the USGS's resource assessments.

Communicating the USGS's results to the nontechnical policymaking audience is a problem that must be solved either by a liaison staff in the Director's Office charged with improving the communication function or by some other means. Because the assessments are predictive, intelligent use of exploration models is essential.

Peer review of CUSMAP and MRA results by industry geologists would benefit both programs and improve communication and cooperation between the two groups.

This Nation's industrial policy (or the lack of one) and the plight of resource-impoverished future generations are issues that bother this speaker, but they are probably not the proper subjects for this workshop.

DISCUSSION GROUP 1A

THE ROLE OF MINERAL RESOURCE ASSESSMENTS IN PUBLIC POLICY FORMATION

By D. Christopher Findlay[1] and Jack Schanz[2]

SUMMARY

The demands for resource assessment in the United States and Canada will continue in the future; as a consequence, the role that assessments will play in public policy formulation (particularly land use planning policies) is likely to become more influential. Demands that the results of assessment projects be expressed in quantitative format will increase.

To be credible in the public perception (and thus in the political arena), resource assessments must be effective tools, but they must not be seen as a part of advocacy. The technical results of assessment projects need to be presented in clear, nontechnical, unambiguous formats to be useful in formulating policy. In addition, a continuing education process is critical to promote mutual interaction between the scientists doing resource assessments and the clients and users of such assessments.

INTRODUCTION

A resource assessment can range from a broad-based examination of a nation's mineral endowment to a specific judgement as to whether the characteristics of a designated area suggest that certain types of mineral deposits do or could occur on that tract and should be considered in planning for its future public or private use.

The users of or audiences for mineral assessments vary. There are those who are responsible for strategic planning to ensure a nation's economic and military security and who are concerned about the current and future mineral supply stream, both indigenous and foreign. A mineral-producing firm uses mineral assessment data to guide an exploration program from its initial regional focus toward site-specific selection for detailed exploration. State, Provincial, or Federal land use planning or management agencies need to make single- or multiple-use decisions among various alternatives or competing uses. Agencies responsible for leasing or selling publicly owned mineral resources must determine the pace and appropriate returns to be expected from the disposition of public resources.

Geological surveys are responsible for providing the basic geologic information and qualitative or quantitative assessments used for or as a part of these decisions. This discussion group was not able to pursue all of these factors. On the basis of the technical and information focus of the papers presented at the workshop, it was decided to concentrate on regional, local, or site-specific assessments that have become an integral part of the public land decision process, both in the administrative and legislative branches of governments.

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[2] Congressional Research Service, Library of Congress, Washington, D.C. 20540.

However, the discussion group did not wish to imply that national resource assessments of a strategic nature have been relegated to an inferior position. Geological surveys should continue to make periodic estimates of national resources of important mineral commodities. Such estimates, especially for strategic and critical minerals, should be made available, in clear, forceful layman's language, to those responsible for making decisions on national economic and mineral policy. Although estimates of this type were not the focus of this symposium, we believe that they constitute an aspect of resource assessment that is vital to the national interest; in the long run, their influence on policy decisions may be more dramatic and visible than that of regional assessments (for example, wilderness, park, or CUSMAP). It is thus important, despite variations in public interest in mineral supply problems, to maintain a continuous, long-term program in this area.

DISCUSSION

In examining the role of resource assessments with regard to public policy formulation or specific resource decisions on public lands, the group directed its attention toward the effectiveness of introducing the results of such assessments into the process. In Canada, assessments are incorporated into the national parkland allocation process at a relatively early stage, as the refinement of land use decisions reflects (for example, changes in park boundaries). In the United States, some land use allocations or withdrawals predated the availability of more sophisticated assessments. Because there has not always been an orderly process for considering mineral potential, much of the work of the U.S. Geological Survey (USGS) and the U.S. Bureau of Mines is being introduced at a later stage in policy formulation or decisionmaking, and its impact is less certain.

Key concerns include (1) the degree and character of quantification found in assessments; (2) the public's perception of the relative importance of minerals and their assessments in the policy decisions made; (3) the degree of confidence that both supplier and user have in the assessment; (4) the mechanisms (both formal and informal) that are available or should be available to introduce the assessments into the policy-generation process; (5) the translation of scientific and technical data and analysis into a form and language that are usable and understandable by the decisionmakers; and (6) the need for the government analyst to take a more active role in presenting mineral viewpoints and priorities to ensure that these elements have equal status and visibility in what is ultimately a political decision.

Quantification

Quantification has become common in appraising national resources such as the reserves and resources or the future importance of seabed minerals, but, in the group's judgement, the amount of quantification attempted in local or regional mineral resource assessments requires considerable caution. Given the nature of the data available, the fragility of the analysis, our current capabilities, and the nature of the decisions being made, it may be inappropriate and perhaps unnecessary to assess relatively small areas in terms of numbers of discoverable deposits, grades and tonnages, probabilities of occurrence or discovery, and so forth. The group did recognize, however, that the trend toward quantification is inevitable and that demand will increase in the future.

The land use or policy decisionmaker demands (and does need) an impression of the order of magnitude of the mineral resource potential at hand, in terms of gradation from high potential to low to little or none. Moreover, the character of the deposits that may be found needs to be presented in terms of understandable magnitudes. Examples of the median discoverable size for various commodities should be included to illustrate their significance for commercial opportunities to enhance future supply.

Public Perception

A common feeling among geologists working on assessment projects is, "Nobody pays any attention to our stuff anyway. Why bother?" Is this true? Probably not, in the long run, although it may seem so sometimes. What is apparent, however, is that the degree of importance that the "system" assigns to the assessment process is in direct proportion to how important the public (and the media) perceives the problem to be. This correlation was amply demonstrated by the petroleum resource appraisals of the 1970's, when the OPEC crisis precipitated a frantic concern about domestic petroleum resources and the degree of "independence" from the OPEC cartel that could be demonstrated by petroleum-producing countries. To a lesser degree, the same phenomenon manifested itself in the Club of Rome and the 1972 "Limits to Growth" days, when Western nations suddenly became aware of the possibility (believed in by many at the time) of diminishing supplies of natural resources, including metals.

In the intervening two decades since Garret Hardin's "Tragedy of the Commons" exercise and the decade plus since the Meadows Group exercise in the "Limits to Growth," perceptions of resource supplies have shifted dramatically. No longer do the large, global concerns of resource supplies engage public and media attention. The spotlight has shifted onto other global concerns. People involved in resource assessment are now in the shadows, slogging on, unnoticed by most. The concerns are more prosaic, more local, demanding little attention on the world's stage. Land use planning is a pale echo against Malthusian doctrine.

Degree of Confidence

The influence that a project result may have on the generation of policy is in direct proportion to the degree of confidence with which the results are presented. If the results of resource assessments are presented in a caveat-riddled fashion, they are not likely to be given serious attention by those in authority and those generating policy stances for complex questions. Scientists are conditioned, by temperament and training, to be cautious. This conditioning is a strength, but it can also be a weakness. If, after spending collective hours, days, and months putting their best professional efforts and judgements into an assessment project, scientists present their results without the strength of their convictions, the persons and systems that they are attempting to convince will know it.

On the other hand, confidence based on unsound and unscientific evidence is not to be encouraged. Rather, in the scientific manner, the degree of confidence should be quantified. The quantification of confidence (confidence levels) provides the only objective yardstick by which the nontechnologist (that is, the policymaker) can make relative judgements about the usability of conclusions in a policy analysis. Such judgements are made by honetsly evaluating the confidence levels provided by the scientists that have conducted the assessments.

Translation and Communication

It is quite apparent that a mineral assessment has to be converted from its original detailed scientific mode into a digestible package, in terms of both length and style. This package needs to be transmitted formally, but, wherever possible, it should be accompanied or preceded by an oral presentation to those directly and actively involved in the land use decision process. If the package is also accompanied by public release and explanation, so much the better.

Effective communication of mineral resource information requires early input into both the administrative and the legislative processes. The emerging mineral resource problems, the questions that need to be asked, and the character of the response both in time and content need to be identified early on. Although a formal process needs to be defined, there is no substitute for informal communication with both the administrative and the legislative elements as the process proceeds.

Mechanisms

After an erratic start, formal mechanisms for producing resource assessments and for incorporating them into the process of policy formulation and decisionmaking seem to have become established (more or less) in the United States and Canada. These formal mechanisms are far from perfect, but, over the past few years, they have become at least institutionalized to some degree. Common complaints include (1) not enough lead-time warning for assessment requirements, (2) insufficient appreciation on the part of planners of the complexities and time necessary to mount a serious field-based assessment project, and (3) the propensity for planners to change plans on short notice, without appreciating the factors just mentioned. These negative aspects are gradually being overcome with time and experience. A key element is the operation of "informal" mechanisms whereby staff in participating agencies (that is, governmental operations and resource agencies) are made aware of the operational problems and mandate factors with which companion agencies must deal. Although the systems are far from perfect, time, experience, and increased awareness of interagency preoccupations seem to be gradually improving the situation. Further reinforcement could come through a planned program of education and information about mineral resources and their assessment for policy analysts, legislative staff, and administrators who must deal with resource issues.

Advocacy

Each government has its own system for deciding when and how basic data inputs are made. There must be an "advocate," "spokesperson," or "educator" for each element or interest that needs to be heard or perhaps accommodated in the resource decisions to be made. As a consequence, both within the government agency and in the public arena, someone must present the mineral resource necessities and points of view by explaining the situation and making a case for recognizing the consequences of decisions and for pointing out alternatives.

In the United States and, to some degree, in Canada, the agencies that are responsible for mineral resource assessments and that contribute to the subsequent use of these analyses are reluctant to explain and promote appropriate recognition of mineral resource estimations. In contrast, some agencies responsible for other land use alternatives tend to be more closely identified with and involved in management and administrative decisions encompassing their jurisdictions.

Concurrently, in the political and public opinion arena, mineral resource firms, local interests, and the relatively small labor forces required by the mineral industries are either not inclined to represent the mineral resource viewpoints, like other resource or environmental interest groups do, or else they are not as effective. Federal agencies responsible for mineral data and analyses cannot in any direct way overcome such perceived deficiencies of representation. On the other hand, to assume a passive role in the internal and intra-agency consideration of mineral problems and use of assessments in this process does not seem appropriate. An active role in the consideration of mineral resources is an internal role, one that cannot be extended into the public arena once the policy decision or position of the responsible Federal agency has been determined internally. To do otherwise would soon erode confidence in the credibility of the mineral assessment groups.

CONCLUSIONS

Demands for resource assessment will continue in the future, both in the United States and in Canada. As a consequence, the role that assessments will play in public policy formulation (particularly land use planning policies), is likely to become more influential.

The U.S. Bureau of Land Management is responsible for some 376 million acres. Approximately 12 million acres has been scheduled for assessment as wilderness areas. The process of evaluating and designating public and private lands in the United States will require the continuation of assessment programs (including CUSMAP) involving the USGS well into the 1990's. In addition, national forest lands total some 192 million acres, much of which may eventually require assessment projects (by the USGS) into the mid-1990s and beyond. To date, some 45 million acres have been assessed.

In Canada, current northern assessment programs conducted on Federal lands in the northern territories by the Geological Survey of Canada are expected to continue into the late 1980's. New land use planning programs, now in the formulative stage, are expected to add a significant new component to current programs. Other projects conducted for more specific purposes, such as the assessment of massive sulfide deposits on the sea floor off Canada's western coast (Juan de Fuca Ridge) will demand more attention, probably well into the 1990's.

Demands that the results of assessment projects be expressed in quantitative format will increase. Such estimates are likely to be more influential in policy generation than qualitative estimates will be.

The trend toward quantification of resource estimates is considered to be inevitable. In spite of the discomfort that many scientists feel about casting difficult predictions in even more difficult quantitative formats, the legitimacy and credibility of the process (as input to policy formulation) may ultimately depend on this development. Partial quantification of current, essentially qualitative techniques can be achieved by applying grade-tonnage models to estimate the range of grades and tonnages of particular deposit types considered to be permissive for particular "target" geologic environments. The development of credible probability-of-occurrence models is considered a much more formidable task but will have to be pursued.

As our report noted earlier, particularly in the context of national-scale estimates of strategic commodities, we feel that such estimates will have to be quantitative to have any substantial impact on policy generation.

To be credible in the public perception (and thus in the political arena), resource assessments must be effective tools but must not be seen as a part of advocacy.

This topic is difficult and can generate much discussion. An agency conducting resource assessments (for example, a geological survey) may derive conclusions and recommendations concerning an issue such as the disposition of native lands on the basis of its assessments, and such recommendations may be used internally to develop a departmental policy on that issue. Such recommendations should not, however, be part of the public record of the resource assessment. The agency producing the assessments should not play, nor should it be perceived as playing, an advocacy role (for example, on behalf of the mineral industry) in the assessment process. Its function in the process is to be politically neutral.

The technical results of assessment projects need to be translated into clear, nontechnical, and unambiguous formats to be useful in formulating policy.

Policymakers, generalists, and senior bureaucrats cannot make effective use of complex scientific and technical information and conclusions in formulating policy unless this information has been put into plain language and unless the policymakers clearly understand the sense and implications of the assessment results. We believe this translation process can best be achieved verbally (through briefings, "dog and pony shows," and so on) as well as through written communications. In this process, the development of informal communication networks (among agencies, legislative staff members, and so on) is important.

A continuing program of planned education is critical to promote a mutual interaction between the scientists doing resource assessments and the clients and users of such assessments.

Although not specifically discussed as a separate element by the group, the education process is inherent in the general notion of translation and communication. The processes by which planned education could be achieved range from continuing producer-client dialogue through more formal information-exchange mechanisms such as conferences, workshops, and seminars to the introduction of this important topic in college and university courses treating resource assessment, policy analysis, and related matters.

DISCUSSION GROUP 1B

ESSENTIAL ELEMENTS IN IMPROVING THE USE OF MINERAL RESOURCE ASSESSMENTS IN PUBLIC POLICY FORMULATION

By David A. Brew
U.S. Geological Survey

SUMMARY

The preparation and use of mineral resource assessment have changed dramatically in the last 20 years, but further improvements in communication and in policy development and application are demanded if mineral resource assessment is to be truly effective.

The usefulness of mineral resource assessments depends on whether the user understands the information. The provider must present the information and selected analyses in a form and context that are meaningful to the user. The usefulness also depends on whether the information provided meets the needs of the user. Primary and secondary users of mineral resource assessments need to be clearly identified and their specific needs explored through direct discussion. Communication between information users and information providers would be improved significantly by increased personal interaction at levels throughout the mineral resource assessment and economic evaluation processes. It would also be improved by providing four types of reports: (1) a technical geoscience report, (2) a technical mineral economic evaluation report, (3) a short report on nontechnical highlights and results, and (4) a nontechnical public news release.

The success of a mineral resource assessment report can be measured by (1) its scientific credibility as determined by peer review and other accepted standards, (2) its effectiveness as a communication effort (that is, the right information was in the right place at the right time), and (3) its actual usefulness to the users. These three measures should be monitored both continuously and retrospectively.

Mineral resource assessment is essential to a national mineral policy designed to assure sufficient mineral availability for our society to function properly. The policy should be expressed in wise public decisionmaking, including decisions on land use, exploration, and investment. A critical part of the framework for such a mineral policy is the identification of those mineral commodities that are of primary importance to the nation or other jurisdictions. A clear statement of the policy and an appraisal of its effectiveness are required.

INTRODUCTION

The preparation, communication, and use of mineral resource assessments constitute a complex system that is of increasing importance in the United States and in Canada. The system contains two end members—the information providers and the information users—who are linked together by a communications bond. The system is represented in figure 1, which identifies major components of the information-provider side and of the information-user side. All parts of the system can be improved and some

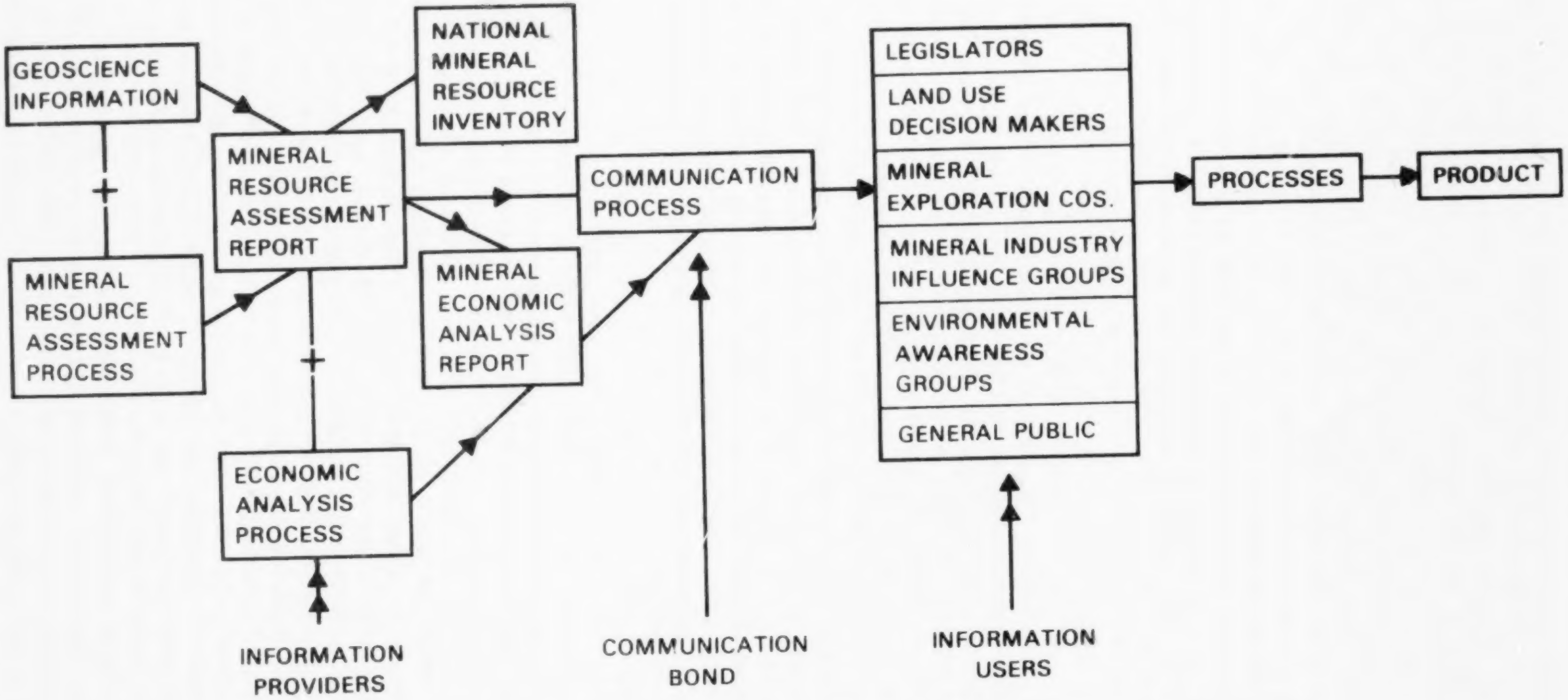
GEOSCIENCE INFORMATION
MINERAL RESOURCE ASSESSMENT PROCESS
MINERAL RESOURCE ASSESSMENT REPORT
NATIONAL MINERAL RESOURCE INVENTORY
ECONOMIC ANALYSIS PROCESS
MINERAL ECONOMIC ANALYSIS REPORT
COMMUNICATION PROCESS
LEGISLATORS
LAND USE DECISION MAKERS
MINERAL EXPLORATION COS.
MINERAL INDUSTRY INFLUENCE GROUPS
ENVIRONMENTAL AWARENESS GROUPS
GENERAL PUBLIC
PROCESSES
PRODUCT
INFORMATION PROVIDERS
COMMUNICATION BOND
INFORMATION USERS

FIGURE 1.--Conceptual framework linking resources information providers to users.

parts must be improved if mineral resource assessment is to be effective in public policy formulation and to become a major influence on the use of public lands.

The overall mineral resource assessment preparation-communication-user system has improved greatly since the earliest efforts. The most dramatic improvement, which has taken place in the information-provider part of the system, has resulted from the development and implementation of better field and laboratory geologic, geochemical, and geophysical techniques and from the creation and application of both mineral deposit and tonnage, grade, and number models. All of these techniques have been applied to the assessment of undiscovered resources. Research in this preparation part of the system is vigorous; this report therefore deals largely with the "communication" and "user" parts of the system and with public policy.

The essential elements referred to in the title of this report are discussed below in terms of (1) an objective and (2) an approach to that objective. We begin with the policy aspects, which define the overall framework, and proceed to the other elements.

POLICY

Objective: To identify the mineral commodities that are of primary importance to the present and future well-being of a nation (or other jurisdictional level) and to apply that information in wise public decisionmaking. Application of such policy information is appropriate in land use management, exploration incentives, investment incentives, export controls, trade negotiations, and settlement of jurisdictional disputes. These applications should assure sufficient mineral availability for a society to function properly.

Approach: Criteria should be developed to better identify those mineral commodities that are of primary importance to a nation. High-level officials should clearly state the manner in which they expect their subordinates to work toward the goals of government mineral policy. Emphasis should be on data development and communication between appropriate agencies. Those responsible for policy should regularly appraise the degree to which the policy goals are being achieved.

USER CONTEXT

Objective: To provide mineral resource assessments to users in terms that fit into their frames of reference. Because different users have different frames of reference, the mineral resource assessment results must be presented appropriately. These frames are a combination of experience, education, needs, and other factors.

Approach: Providers need to present and explain mineral resource assessment results in terms that the user can understand. It is appropriate to refer to places, objects, items, and other things that are familiar to the user, and it is necessary to confer with the user to learn what references are appropriate. For a geologist, terms of reference include deposit models and other specialized technical material. To a nongeologic user, such terms of reference may be counterproductive, because they involve unknown or poorly understood concepts. Comparison of resource values requires terms that are familiar or known. For mineral resources, the terms of reference may be economic values and may include estimates of overall dollar value, comparisons of a resource in one place with similar resources in other places, and answers or responses to basic questions like, "Why is this important?"

Mineral resource assessment providers are usually willing to identify relative probability in a nonnumeric or nonprobability form and, more often now, in terms of statistical probabilities. However, some means is needed to convey the economic significance of the results, and an economic evaluation is usually appropriate.

USER NEEDS

Objective: To define the end products or use of a mineral resource assessment, so that all of the information can be interpreted and packaged in a report in the format and detail required to support the user's specific needs in a timely manner. Identifying the users' long-range needs allows the providers of mineral resource information to schedule work far enough ahead to have that information ready when it is needed. Providers should prepare the appropriate level and type information needed.

Approach: One approach to this issue is to identify general situations in which the results of a mineral resource assessment can be used, such as in the legislative process, land management planning, and mineral exploration.

Legislatures establish boundaries for designated areas, such as wildernesses and national parks, which withdraw areas from mineral exploration and development. Mineral resource assessments should be displayed primarily on maps or in similar forms, so that the boundary relations can be clearly understood. Data should at some point be summarized in units that relate to other national issues, such as jobs, economic health, and strategic minerals.

Land management agencies need data on the resources within their jurisdictions to prepare long-range plans that (1) provide a level of development that will allow commodity production in an environmentally sound manner and (2) retain a certain amount of area in an undeveloped state. The decisionmaker usually relies on the planning team for the plan analysis. The planning process itself is governed by a set of guidelines that specify some of the characteristics of the resource data. The mineral resource assessment must meet these guidelines to be useful in the analysis and preparation of management alternatives, or there will be little opportunity to include minerals considerations in the final decision.

The mineral resource assessment should be accompanied by some analysis of its significance. The planner must know how important a given mineral-bearing domain is in relation to other mineral-bearing domains both within the planning area and elsewhere. When tradeoffs must be made, it is then possible to trade off the less important area.

Information must be readily related to the other resource data. Comparable maps, scales, and planning areas will place the mineral resource assessment on a more nearly equal footing with analyses of other resources. Units of measurement should be as concrete as possible. Abstract terms such as high and low do not compete well with terms such as dollars, board feet, and miles when the impacts and effects of a given activity are being analyzed.

Industry uses geologic maps and mineral information to aid in their interpretation of favorability and their determination of exploration targets. This information can be communicated in the conventional geologic, geochemical, and geophysical media.

Another approach is to deal with specific known needs. A first step toward identifying specific user needs in the United States has recently taken place. A four-agency task force consisting of the two major suppliers of mineral resource information—the U.S. Geological Survey (USGS) and the U.S. Bureau of Mines (USBM)—and the two major users of this material—the U.S. Forest Service (USFS) and the U.S. Bureau of Land Management (USBLM)—was formed. One objective of this group is to develop a memorandum of understanding that will identify the long-range needs of both the USFS and the USBLM. The task force also plans to meet with congressional committees to ascertain what mineral information they need for legislative purposes.

The USFS is planning to meet with both the USGS and the USBM to discuss the specific types of mineral information needed in its forestwide studies. Since the recent shift to more regional studies, land planners in the USFS are eager to clarify their exact needs at an early stage.

COMMUNICATION MEDIA

Objective: To provide appropriate mineral resource assessments in appropriate forms to all primary and secondary users. Given the obvious differences between the likely users of mineral resource assessments (see fig. 1), no single report or document can be totally effective for all users. Therefore, an important objective is to define an assemblage of reports that will accommodate different needs but at the same time not pose an undue burden on the information provider. An essential accompanying objective is to develop personal channels of communication, at all levels, between the providers and users, so that reports are both adequate from the provider's view and responsive to the user's specific needs.

Approach: The personal channel of communications objective is fundamental to the continuing improvement of communication. Both provider and prime user groups should begin by ensuring that counterparts at all levels become personally acquainted. They should continue by holding early joint discussions of both user needs and provider products, each displaying appropriate examples. Personal consultation should continue throughout the project's lifetime, along with possible exchange of interim information. Preparation of final products by the providers should incorporate suggestions from the prime users.

The assemblage of reports documenting the assessment theoretically should vary according to the intended prime user; in practice, the results of any given mineral resource assessment are also used by others. Consequently, every assessment needs to be represented by four types of reports: (1) a scientifically credible, peer-reviewed, technical report that is the hard documentation of the assessment; 2) a credible, peer-reviewed economic analysis report that builds on the results of the assessment and applies exploration, development, mining, processing, transportation, reclamation, and environmental impact factors to evaluate the present and future economic status of both discovered and undiscovered resources; (3) a brief nontechnical summary report that highlights the main results of both the mineral resource assessment and the economic evaluation report; and (4) a news release or public notice designed to inform the general public of those same results.

These four reports document the scientific basis for the assessment, present the economic evaluation of the resources, and convey in nontechnical terms to decisionmakers and the public the highlights of the assessment and economic evaluation.

MEASUREMENTS OF SUCCESS

Objective: To measure the success of mineral resource assessments as completely as possible. For a mineral resource assessment report to be considered a successful undertaking, it should be examined in the context of the purpose for which it was intended. Some retrospective review should be included. Ideally, assessments are an iterative process, and iterations are one kind of hindsight study . One important question concerns the time interval for the iterations.

Approach: A well-designed report should (1) provide meaningful technical data supported by reasonable conclusions that can withstand close critical examination by an author's peers as well as by the scientific and political community; (2) be completed at the right time (namely, the due date); and (3) fit the needs of and be understandable by the intended user. Both restrospective and current studies should be made to determine if the methodologies used created reports available to the user at the proper time and provided the information needed.

Success should not be measured by the fact that an area was withdrawn or a boundary changed. The placement of an area into the wilderness category even though a mineral resource assessment indicated that significant mineral deposits were likely to be present, is not necessarily an indictment of the report. Other nonmineral resource values may have been more important in the judgement of the land use decisionmakers. It may also be that the report was not delivered in a timely fashion.

Similarly, attempts are sometimes made to measure the success of a mineral resource assessment by counting the number of new discoveries that it precipitated. Such an evaluation is usually not possible, because the land is or was effectively withdrawn from mineral entry. If the area remained open for exploration, one valid measure of rating the assessment might be the degree of exploration interest that resulted. Another measure might be the number of new mining claims recorded.

DISCUSSION GROUP 4

EXPERT SYSTEMS (AI): A LINK TO ECONOMIC AND POLICY ISSUES

By John C. Houghton and Richard B. McCammon
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SUMMARY

The quantitative aspects of resource assessment are moving toward artificial intelligence (AI) applications. However, because of the current high cost of building, testing, and maintaining expert systems and because of the present ad hoc and brittle nature of these systems, proven AI systems for resource assessment have yet to be developed.

INTRODUCTION

The first successful application of artificial intelligence (AI) in resource assessment was the PROSPECTOR system, developed by Stanford Research International and funded largely by the U.S. Geological Survey (Duda, 1981). The visibility of PROSPECTOR has increased the awareness of the potential of expert systems in resource assessment. In addition, AI applications in other fields make the future for AI appear bright. Several thousand single-purpose, artificial intelligence-oriented, microcomputer workstations have been sold to financial and earth science companies. The costs of storing and processing digital information are becoming cheaper, and the trend is likely to continue.

With these prospects in mind, our discussion group investigated the types of information required by users of resource assessments and the potential for artificial intelligence, or expert systems, to provide that information for resource assessments of public lands.

DISCUSSION

We began our discussions by listing the types of models necessary to provide a decisionmaker with the information that he needs. We next considered the advantages and disadvantages of using expert systems in resource analysis applications. Finally, we proposed case studies that could test the utility and feasibility of expert systems for such applications.

The Link to Policy

One of the themes of this conference was the need to provide useful information to decisionmakers in a form that will enable a nonscientist to balance the tradeoff between the mineral resource potential and other values. Although other groups studied the link between resource assessments and policy analysis specifically, their results were not available to our discussion group.

The types of models necessary to provide those values are shown in table 1. The endowment models are the most familiar to geologists. In their simplest form, they are maps on which areas of favorability have been outlined. Our group called these "blob maps," but they are also called "hot dog maps" or "areas of favorability" (Richter, 1975; DeYoung, 1978).

A more sophisticated version of the endowment model includes information on the location of the deposits (similar to "blob maps"), the statistical distribution of the tonnage and grade of deposits, and the expected number of deposits in an area. These models make use of either genetic concepts or occurrence probabilities in the assessment process. Other types of information, such as depth, mineralogy, and geometries, are important properties to include in these endowment models. It might be possible to develop resource assessment models that bypass part of the above process by generating occurrence maps (which we have termed "isoblob maps") that express the probability of discovering one or more deposits within a specific area.

Another type of model is the discoverability model, which relates the amount of effort expended to the amount of resource discovered. Such models are being generated for oil and gas (Attanasi and Haynes, 1984) but have not yet been constructed for mineral resources. Production models, typically developed by the U.S. Bureau of Mines, refer to the cost of producing a deposit as a function of considerations such as tonnage and grade. Finally, consumption models estimate the effect of mining or not mining a particular deposit on economic indices such as the gross national product (Office of Minerals Policy and Research Analysis, 1981).

TABLE 1.--Flow of analysis from policy to geology

Tasks	Status	Examples
Endowment models---	Mineral resource potential maps ("blob maps").	Traditional geologic assessment.
	Location, tonnage and grade models.	Occasional
	Genetic models; depth, mineralogy, and shape.	Research
Discoverability---- models.	Dollars per acre; tons per acre; feet drilled per ton; and so on.	?
Production models--	Engineering cost models	Existing (U.S. Bureau of Mines).
Consumption models-	Supply and demand models; input-output models; effects on gross national product.	?
Policy decisions,-- land use decisions.	Decision memos	Active

It is important to match the type of model with the information required by the decisionmaker. In the preliminary stages of land use decisionmaking, for instance, "blob maps" might be sufficient for preliminary decisions on whether to consider a given parcel of land for further analysis.

Expert Systems

This report treats expert systems as synonomous with artificial intelligence. In fact, expert systems are a subset of the field of artificial intelligence. By an expert system, we mean to distinguish AI computer programs from the more traditional computer programs that match given data with a library of analogues. An expert system tells the user not only which analog is most similar but gives expert advice on why one set of observations was chosen over another. This capability distinguishes expert systems from other forms of analysis, such as pattern recognition and discrimination nets.

Expert systems are usually executed in either one of two modes--consultation or batch. The basic strategy of the PROSPECTOR system was to act as a consultant to geologists providing information about mineral deposit types. A geologist assessing an area could interact in this mode by computer with a number of experts. Although a batch mode has more potential, it is more difficult to achieve. In batch mode, the computer acts both as the expert and as the field geologist; that is, it both collects data on the area to be assessed and draws inferences from available data. Typically, batch mode is applied on a cell by-cell basis within a given area.

Advantages

In discussing the ways in which AI could substitute for more traditional modeling, the group listed the advantages and disadvantages of the potential uses of AI. The primary advantage is that the knowledge and inference capabilities of geologists having expertise in a particular area of inquiry can be built into an expert system that can be used by other geologists. It opens up to the user a fund of knowledge about mineral resources beyond the grasp of an individual geologist. There are now over 100 mineral deposit models, and no geologist can be expert in all of them. An expert system affords the means to match the data with all the deposit models so far developed. Using this process, geologists can be trained more effectively in the recognition and evaluation of mineral resources.

AI represents an unstructured approach to resource assessment. It is a technology for dealing with incompletely understood ideas, so it is appropriate for the complex and uncertain task of mineral resource assessment. Because mineral resource assessment has few fixed rules, however, a high level of expertise is required at each step of the process.

Computer processing is becoming more inexpensive. Storage requirements and numeric processing that would have made an expert system expensive only a few years ago are now inexpensive in comparison with other costs of gathering geologic data. A side effect of the decreasing expense of computer processing is that geologists are turning more frequently to microcomputers and automated data processing. Current work environments more typically contain computerized data processing, digitized maps, and computerized analyses that result in time savings, increased efficiency, and greater productivity.

The use of expert systems probably expands the range of mineral deposit possibilities considered by a geologist making an assessment. Harris (1984) found that applying an expert system to an area already assessed increased both the expected amount of resources and the uncertainty, even when virtually the same data and rules were used. Conditions recognized by the expert system as favorable for additional types of deposits were not recognized as such without the expert system and thus were not considered in the earlier assessment.

Expert systems can sometimes provide increased rigor in the analysis. At any point in a consultation mode, for instance, the user can determine what rules and what data are influencing the final probability of occurrence. A certain discipline is required by an expert geologist during the eliciting of information regarding rules and rule strengths. This increased discipline has been cited as perhaps the most important aspect and benefit of PROSPECTOR.

A single expert system containing many genetic deposit types has the potential to produce estimates that are more consistent than other local ad hoc methods. Universal use of expert systems would help integrate resource assessments, but at some cost. Resource assessments using different techniques or made by different people, particularly when they are made in the same environment, are often too concentrated around a single value. As a result, the true uncertainty (the cost) is often greater than the uncertainty presented.

When reading descriptions of genetic models without the tutorial approach of an expert system, it is difficult to discern the relative importance of each of the deposit model's attributes. Expert systems are more fun and generally easier to use, because geologists who use expert systems are guided through the material as they ask specific questions. The consultation information is delivered from the expert system to the geologist when he is questioning a given step in the evaluation process. This capability makes expert systems efficient learning tools.

Geologists can influence the outcome of an interrogative session with an expert system by using their own knowledge and experience. A comprehensive set of genetic models contained in the framework of an expert system assures the geologic profession of both the record of the information possessed by contributing experts as well as an emulation of their inferential thought processes.

Disadvantages

Xerox Company personnel, who are experts in AI applications, presented guidelines on the decisions that are successfully modeled by expert systems. A typical decision takes about 30 minutes for an expert system to make. If the decision takes much less than 30 minutes, the expert system is probably more complex than necessary. Decisions requiring much longer would necessitate expert systems that are too complicated and information too detailed to be modeled adequately and efficiently. Many resource assessment decisions take longer than 30 minutes.

Although computers have the potential to analyze great amounts of data, such as those contained in geophysical, geochemical, and geologic maps, expert human beings (sometimes called carbon-based expert systems, or wet computers) are much better able to synthesize three-dimensional and other pattern information. Expert systems, to date, have not been able to analyze spatial data bases as well as they have other objective information such as lithology and mineralization. The way in which an expert field geologist can generalize a geologic map and infer the underlying structure and sequence of events is something that a computer is unlikely to emulate for quite some time.

Even though computing costs are becoming cheaper, developing expert systems is still expensive and time consuming. They require much massaging by the experts and subsequent refining as they are used. Once they are developed, they are not easy to update and keep current. The computer equipment used for expert systems at present is single purpose and relatively difficult to use. AI has its own program languages and often its own hardware design. This constraint may be eliminated some time in the future, however, when perhaps even a common desktop microcomputer will have the same capability as current AI computers, and the software will be powerful enough and user friendly enough to be invisible to most users.

Expert systems are inherently ad hoc and brittle; that is, they are unable to respond well to surprises. Inference nets created by different geologists may look quite dissimilar, even for the same deposit type. The calculations lack some of the structure displayed by, for instance, multivariate statistical analysis.

Finally, there are the usual problems that expert systems share with other methods of resource assessment, including the difficulty in defining an economic occurrence and assessing resources where analogs are poor or nonexistent.

CASE STUDIES

Further testing of expert systems in mineral resource assessment can go in several directions. Test cases can be devised in which research is done to improve the expert system and tests performed to contrast other methods for estimating resources.

Conterminous United States Mineral Assessment Program

One possible test case would be to compare the results of using an expert system with the results of using the more conventional and more accepted approach taken by the Conterminous United States Mineral Assessment Program (CUSMAP). An existing assessment, such as the one that is nearly complete for the Sherbrooke-Lewiston sheet in New England, would be compared with one generated by combining PROSPECTOR-type models with tonnage and grade models. Once the expert system and the tonnage and grade models were in place, various combinations of evaluators and data could be tested. For instance, the same experts who originally evaluated the Sherbrooke-Lewiston area could use all of the original data. They could also try using much less data. Other geologists having strong backgrounds in economic geology but less experience in the Sherbrooke-Lewiston area could use only some of the data and then all of the data. Other geologists much less experienced in economic geology could do the same. Such an experiment would be useful in evaluating the value and efficiency of expert systems and also in identifying and measuring the relative value of data.

An Attempt to Include Spatial Data

One of PROSPECTOR's principal limitations is its inability to use spatial information. Geologists think in terms of maps and can associate univariate and multivariate map signatures with geologic phenomena such as ore deposits. A second case study would prepare an expert system that could receive digitized map input, such as:

- Thematic data (for example, a geologic map).
- Gray tone (for example, topography and remotely sensed data).
- Flight line (for example, aeromagnetic and radiometric data).
- Points (for example, geochemical samples and known mineral occurrences).
- Lineaments (for example, faults and linear features on photography).
- Unconformities.

The "knowledge base" would contain, wherever available, information relative to the spatial attributes of each deposit type as well as the nonspatial attributes, such as minerals present, alteration products, and so on.

A preprocessor would take the various digital inputs and allow the user to choose cell size and shape and to interpolate, register, and filter the various inputs to form a geographic data base. The expert system would provide menus and information about possible choices of method and produce graphic outputs of each data layer at the desired scale and color scheme.

Existing deposit models would be augmented by including descriptions of important spatial characteristics, such as:

oDistance to unconformity.
oPresence of intersecting lineaments.
oLarge-amplitude magnetic and geochemical anomalies.
oGeochemical pathfinders and important element associations.

An anomaly detection processor would contain special-purpose algorithms to be added as they are developed (for instance, Bouguer anomaly data from gravity measurements and the topographic map, geochemical anomalies after subtracting the effects of variation due to bedrock geology and iron and manganese scavenging, and radiometric anomalies after removing effects of granitic intrusives).

The program itself would be in part a user-friendly front end to conventional data processing techniques. In addition, it would use the knowledge base in such a way as to suggest possibilities for a particular model type that would require spatial analysis. For example, the expert system might respond, "My records show that all deposits of type x are within half a kilometer of a major unconformity, generally in association with felsic intrusives, and often with the intersection of major fault zones."

Output would be in the form of a gray-tone map of relative favorability, but it could include other types of intermediate products to aid a geologist in answering questions. Output would include the ability to interpolate and add more speculative information by hand (for instance, interpolating between geochemical anomalies by using knowledge of geologic trends).

FUTURE DIRECTIONS IN EXPERT SYSTEMS

Applications of expert systems to resource assessment have been primarily in the consultation mode. Although expert systems are on the cutting edge of current research and may not be superior to alternatives for some time, it is likely that future expert systems will be applied in the batch mode, which will allow the automated processing of large amounts of data and more broad-scale assessment. For regional applications, a batch-mode AI system can be developed on the basis of a network of small cells, which would allow consideration of spatial trends and autocorrelation of the variables as well as of the multivariate relations between them. Information for small cells can be combined to obtain data for larger cells, which may be of irregular sizes and shapes.

It should be recognized that the lists processed by geologists contain many two-dimensional (map) images as well as three-dimensional information. Techniques to incorporate these two types of information should be further developed.

The quantitative aspects of resource assessment are moving toward AI applications. But, for resource assessments, AI is still an evolving technology. Development of reliable expert systems for resource assessment will require a great deal of effort and, at present, appear a long way off.

A MINORITY VIEW

By William A. Vogely
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As the papers presented at this conference illustrate, there is no agreed or dominant system for making a resource assessment. Since no system presents a reliable estimate, none should be translated into an expert system of an AI nature.

Even though the resource assessments produced by the Mark III system, for example, are highly uncertain, they are not directly usable by policymakers, because they do not attempt to indicate the value of the estimated potential in a deposit by commodity. Such an evaluation can be added by the U.S. Geological Survey and the Geological Survey of Canada by using the same method and approach that they used to make the estimates and comparing the target area to its geologic analog. From the unit regional value approach, potential economic values attached to the estimate for the region can be derived by using the same analog approach. These values would be gross values and could not be translated into net present value, but they would give some guidance to the policymaker as to the values involved in a potential mineral resource area. It is appropriate for the U.S. Geological Survey to make these gross value estimates, because they come from the same data base and the same definition of analog areas used for the estimate of the resource potential. Policy analysts down the line do not have that information available to them and so cannot make even that gross kind of value estimate.

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DISCUSSION GROUP 6

THE TRANSFER TO DEVELOPING COUNTRIES OF EXPERTISE IN MINERAL RESOURCE ASSESSMENT AND MINERAL EXPLORATION

By Hermann Enzer[1] and Jan Zwartendyk[2]

SUMMARY

Transfer of expertise occurs in three principal ways: by providing training to other nations, by providing opportunities for cooperative project work, and by providing consultation and advice. Successful transfer of technology and of expertise at an institutional level depends on the recipient country's ability to absorb the technology. Therefore, donor institutions must ensure that the capacity exists in a less-developed country to sustain such an infusion of technology. The process is a lengthy one and requires that donor countries formulate specific mandates under which their earth-science institutions conduct external programs. In anticipation of the rapid and specific exchange of information and technology that will ensue under these mandates, an international clearinghouse and repository of data should be established, perhaps under the aegis of the Organization for Economic Cooperation and Development.

INTRODUCTION

In years past, mineral exploration in less-developed countries was carried out almost entirely by expatriate geoscientists in private enterprise and government agencies. Many less-developed countries now wish to design their own initiatives in domestic mineral exploration and development and want to see their own professionals play significant roles in developing mineral resources and policies. Often, however, local professionals do not have the necessary skills and experience. The expertise gap between developed countries and the less-developed countries is still formidable.

Knowledge shared between developed countries and less-developed countries is transferred in many ways. The U.S. Geological Survey (USGS)-INGEOMINAS mineral resource assessment of Colombia (Hodges and others, this volume) is one example. Another example is the "Global Deposit Modelling Programme" recently set up under the joint auspices of UNESCO and the International Union of Geological Sciences (IUGS). This 10-year program is to be guided by a steering committee composed of representatives from the United States, Canada, West Germany, Finland, and less-developed countries still to be chosen. The program has two objectives: (1) to compile and publish up-to-date knowledge on mineral deposit models and (2) to transfer this knowledge to less-developed countries for use in mineral resource assessment and exploration.

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These programs are just two of many similar programs and projects that have been conceived over several decades. Lack of clear and consistent success raises three general questions about the transfer of expertise for mineral resource assessment and exploration from developed countries to less-developed countries: (1) how is expertise transferred at present, (2) how well does the transfer work, and (3) can the transfer be improved?

DISCUSSION

U.S. and Canadian foreign policies recognize the principle that aiding less-developed countries in their efforts to raise their standard of living ultimately benefits everyone. Therefore, it is assumed here that transfer of exploration expertise is beneficial, even though exploration successes abroad may at times be unwelcome to mining companies in developed countries.

Transfer of expertise takes place mainly in three ways: (1) by providing training (university courses, visits by expert individuals, seminars, publications, and so on), (2) by providing opportunities to participate with experts in an actual project, and (3) by providing consultation and advice.

How Is the Transfer of Expertise in Mineral Resources and Exploration Currently Accomplished?

If the transfer of expertise is to have a continuing beneficial impact on the recipient less-developed country, one primary condition should be satisfied: the host country must have a stable institutional framework that can accept and use the expertise being transferred. Evaluating this capability before the transfer begins is essential in tailoring products to the mineral resource assessment and exploration needs of the less-developed country. This evaluation may result in a first phase of "institution building," which could range from very specific training in particular scientific fields to overall program design and the establishment of earth-science organizations in the developing country. Although the character of the institution-building phase would vary from country to country, the objective would be to ensure some sort of mechanism for perpetuating the use of newly acquired expertise. The higher the stage of institutional development, the more effective the transfer of information and technology is likely to be. Also, a plausible criterion for judging the effectiveness of such transfers is the degree to which they strengthen existing institutions and thereby ensure that their contribution to the country endures.

Three principal mechanisms for transferring expertise seem to be successful: education, exchanges, and joint project work.

Education

Training programs for local nationals may be an appropriate approach to developing needed competence. Such programs may be conducted in the less-developed country or elsewhere. The character of the training should be more advanced and specialized than that which would be provided as part of the institution-building effort. This stage of the effort, for example, could involve training in methods of conducting geochemical surveys, in contrast with earlier efforts that might have involved relating geochemical information to mineral resource assessments.

Exchanges

Cooperating countries may develop exchange programs in which scientists having similar training collaborate, using a broad spectrum of techniques and methods for resource assessment and exploration.

Joint Project Work

Another effective means for transferring expertise involves its direct application to a current resource assessment problem. This approach will at the same time advance knowledge of the mineral resources of the less-developed country.

Several approaches can use these three mechanisms for transferring expertise to less-developed countries. Individual scientists can play a major role in advancing the capabilities of less-developed countries. Bilateral arrangements between cooperating countries can provide for collaboration among governmental entities to advance a less-developed country's ability to carry out resource assessments. Multilateral efforts that involve three or more governmental entities can be used to transfer expertise. Private enterprise companies pursuing their interests can also assist less-developed countries.

An important example of a successful collaboration is the recently concluded bilateral project conducted jointly by the USGS and INGEOMINAS under the USGS's International Mineral Resource Assessment Program. The project provided assistance to Colombia by transferring information on the use of mineral deposit models and geochemical surveys in conducting programs for assessing mineral resources. Because Colombia has an advanced institutional capability, the joint effort is expected to have continuing value in its programs.

It may take years to learn if transferred expertise becomes permanently incorporated into the programs of a less-developed country. The best choice from the many possible ways in which knowledge can be transferred and the most appropriate timing of that transfer will depend on the host country's situation.

Observations on Current Methods of Technology Transfer

During the formative stages of earth-science and mineral-information institutions in a less-developed country, bilateral agreements with developed countries have proven to be a key factor in technology transfer. These agreements between similar apolitical fact-finding agencies offer several advantages over other arrangements. First, receiving assistance from an agency that shares a similar public service perspective can provide experience in solving a less-developed country's problems. Second, the agency from the developed country can offer a long-term commitment and continuity that are less likely to come from consultants or corporate advisors. Third, the diversity of expertise available from a developed country's earth-science institutions cannot be matched by most other forms of assistance. Finally, open access to information is more likely in bilateral agreements with developed countries, because their scientific agencies are not as encumbered with problems of proprietary data as the private sector would be.

Once a sufficiently advanced institution has been established, several other methods of improving expertise on mineral resource assessment can be quite successful. Multilateral efforts can produce information that can be used by less-developed countries. One example is the Circum-Pacific Map Project of the American Association of Petroleum Geologists, the IUGS, and others. Another example is the International Strategic Minerals Inventory, a cooperative effort of nine earth-science and mineral resource agencies in the United States, Canada, and four other countries. Valuable contributions can be made by individuals, especially in providing training courses and lectures. The mining industry is well suited to transfer exploration technology to less-developed countries through on-the-job training and support of the formal education of local earth scientists.

In aggregate, the public earth-science institutions of developed countries are spending significant sums of money on projects to assist less-developed countries in improving their resource assessment and exploration techniques. Funds for these purposes usually come from external sources and are often in small ("seed") amounts available for brief periods only. Within individual institutions, these constraints lead to a project rather than a program approach to overseas work. Moreover, there is no coordination among institutions to avoid critical gaps and wasteful duplication.

Suggestions for Improvements

Most public earth-science institutions in developed countries operate overseas in a reactive and transitory mode, largely because there is no governmental mandate to do otherwise. Given clear mandates, substantial improvements in assistance could be expected. Therefore, the discussion group recommends that developed countries provide their public earth-science institutions with formal mandates for external programs.

The effects of the current "scattergun" approach to overseas assistance are exacerbated by the lack of coordination between less-developed countries and by the inaccessibility of data and reports from previous assistance projects. Therefore, the discussion group recommends that an international clearinghouse and repository for information on the overseas resource programs of less-developed countries be established under the aegis of an entity such as the Organization for Economic Cooperation and Development.

Enhanced and more efficient transfer of the most modern methods of resource assessment and exploration will result if these recommendations are implemented.

DISCUSSION GROUP 8

ECONOMIC ASPECTS OF RESOURCE ASSESSMENTS

By Brian W. Mackenzie[1] and William D. Watson, Jr.[2]

SUMMARY

Discussion Group 8 focused its efforts on answering three questions: (1) what is the role of economic analysis, and how does it mesh with physical or geologic resource assessments; (2) given the different stages of mineral development (ranging from unknown to delineated deposits) and different geographic settings (ranging from a national scale through smaller areas such as national parks to specific deposits), what are the available economic assessment methods, and what physical resource information is needed for their application; and (3) what are our current capabilities to perform resource assessments, especially economic and geologic analysis of unknown mineral deposits?

In addressing the first question, the group concluded that policymakers ordinarily require dollar estimates of resource values. Dollar values allow explicit and direct comparison of the various effects that alternative policies might trigger. In this context, economic analysis translates physical or geologic measures of resources into dollar terms. More importantly, this translation is probably best achieved when economic and geologic analyses are integrated with each other in the assessment process.

To address issues related to the second question, the discussion group outlined the different dimensions of resource assessment in a policymaking context. Three mineral development stages (short-, medium-, and long-term) and three geographic settings (broad, area, and deposit) are defined. When these dimensions are related to policy issues, they provide a framework for identifying economic assessment methods and the data and analysis needed, in turn, from geologic assessments. The intent of the discussion group was to provide a comprehensive overview of information requirements and linkages.

In reference to the third question on the state of the art, the discussion group concluded that established economic and geologic assessment methodologies are available for evaluating unknown mineral resources (Harris, 1984). Because analysis can be very uncertain, however, the degree of uncertainty should be made explicit wherever possible. The group concluded that we ought to be able to improve our resource assessment capabilities by undertaking assessments and checking their validity (through retrospective studies). Currently, there is a need to supply policymakers with dollar values for unknown mineral resources on public lands where decisions are being made about mineral development and environmental and scenic features. Resource assessments (in physical units and dollar terms) have been completed recently for a few areas in Alaskan national parks and the Pacific Mountain System. These studies, which demonstrate our capability to evaluate unknown deposits, are described briefly in the final section of the report.

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INTRODUCTION

The economic overlay for resource assessment concerns the supply process by which minerals are converted from geologic resources to marketable products. The main elements of this process are geologic stocks of resources, concentrated in mineral deposits, which flow through a multistage series of mineral sector activities to a minerals market.

Various types of resource appraisal are carried out to examine the physical occurrence and availability of actual and potential mineral stocks. Assessments of the cost, risk, and return characteristics of mineral exploration, mine development, mining, mineral processing, and transportation reflect the economics of the sequential conversion process. Finally, commodity economics concerns the documentation and projection of mineral market conditions—supply, demand, and price factors and their interaction—in the context of minerals markets.

Government responsibilities relating to this mineral supply process give rise to the demand that various public policy issues be examined. A system of geologic knowledge and expertise—in the form of mineral resource assessments—is required to address these concerns.

In his presentation at this workshop, Larry Drew used a grappling-hook analogy to raise questions about the connections between mineral resource assessments and public policy needs. Our group concluded that policymakers want to know the consequences of policy options measured in terms of a common metric. More often than not, this measurement translates into dollar values. For mineral resources, dollar values can be obtained by the interdisciplinary application of both economic and physical resource assessment methods. Neither alone is sufficient; both are required for the policy connection. These interconnections—building on Drew's analogy—are illustrated in figure 1. Economic analysis forms a grappling hook that connects the physical aspect to policy needs. Throwing a grappling hook back to secure the connection in the opposite direction, economic analysis requirements define the types of geologic resource assessments that are necessary. (Some members of the discussion group felt that mineral resource assessment and economic analysis on public lands are irrelevant to public policy. These members pointed out that the mineral industries in the United States and Canada are in an economic downturn. Public policy, as it is currently focused, will have little or no effect on the economic outlook for the minerals industries. In these circumstances, there is no need for physical and economic resource assessments on public lands.)

Our group considered our topic to be distinct from but closely related to that of Discussion Group 1 (The Role of Mineral Resource Assessments in Public Policy Formulation). We assumed that Discussion Group 1 would deal with human relations and organizational aspects of the resource assessment-policy formulation interface, whereas we would concentrate on economic analysis aspects of the connection.

DISCUSSION FRAMEWORK

This section establishes a framework for discussing various dimensions of mineral resource assessments (including economic analysis) within the context of public decisionmaking. Our intention is to establish terms of reference to cover the entire subject area.

A first and very important part of our framework follows directly from the grappling-hook analogy shown in figure 1. In many situations, public policymakers would like to be given mineral resource assessments, expressed in terms of both physical and dollar units, in order to weigh the consequences of alternative actions. The various informational linkages, as shown in figure 2 are:

oIdentification of public policy needs (to include mineral policy issues of joint and individual interest to Canada and the United States).

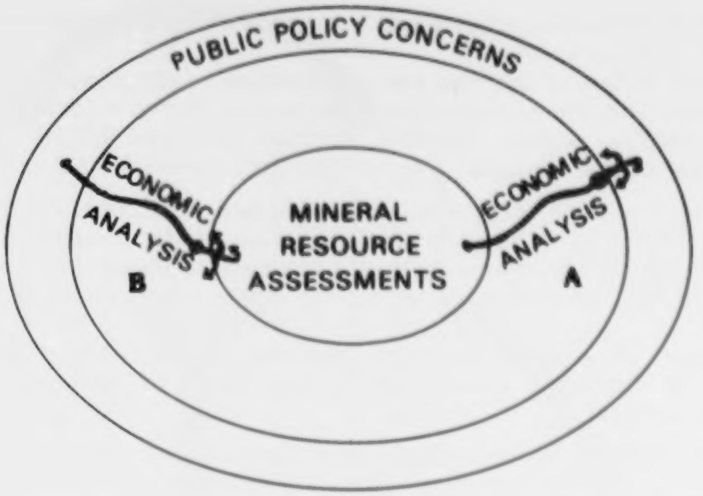

FIGURE 1.—Economic aspects of resource assessment. A indicates the resource aspects of economic assessments; B, the economic aspects of resource assessments.

- Resource assessment requirements (to include methods and scope to meet information requirements for economics analysis or information requirements directly pertinent to policy needs).
- Economic analysis requirements (to include methods and scope appropriate for analyzing specific alternative actions).
- Geologic analysis requirements (to provide data and analysis focusing primarily on physical dimensions for use in economic analysis or for direct use by policymakers).

By their very nature, resource assessments involve both geologic and economic aspects. This requirement is easily understood, for example, in terms of the geologic and economic axes of the McKelvey box diagram (McKelvey, 1972; U.S. Geological Survey, 1976). For public policy needs, it is important (indeed essential) that both aspects be made explicit. Otherwise, policymakers will have only a vague understanding of resource values and the opportunity costs of alternative policies. As figure 2 shows, policy issues and the needs of policymakers establish the frame of reference for resource information. The form and scope of the economic and geologic resource assessments should be designed so that these information needs are met. The discussion group also concluded that resource assessments would almost always require interdisciplinary study. Economic analysis, for instance, helps to define the scope and type of mineral resource information necessary for its completion. Likewise, the physical mineral resource assessment must be related to mineral prices, marketing prospects, and extraction costs in order for it to have clear meaning. Sometimes, however, it may not be possible to include economic analyses as an explicit informational component (as illustrated in fig. 2 by the lower path between policy needs and geologic analysis, which bypasses economic analysis). Such an exclusion can occur when very little physical resource data are available. In these cases, very rough measures of resource values based primarily on geologic assessment are all that can be estimated.

In addition to these information elements, we also use two other dimensions. The first is a spatial dimension designed to identify policies and appropriate information requirements for different geographic units as follows:

- Broad, which indicates policies and information requirements at an international, national, or regional level.
- Area, which indicates policies and information requirements at a level of detail between broad and site specific (for example, a proposed wilderness area).
- Deposit specific, which indicates policies and information requirements for specific deposits (for example, a known, publicly owned deposit offered for lease).

The first two spatial categories—broad regions and areas—can be defined either geologically or politically. Our notion of a broad region includes broad exploration environments, States, and Provinces, covering hundreds of thousands of square miles. We consider areas, on the other hand, to vary from a few square miles to several thousand square miles.

The second dimension of the discussion framework relates to time considerations. In this case, time refers to the stages of minerals development and includes three categories:

- Short term, meaning currently installed and available productive mine capacity.
- Medium term, meaning known but presently undeveloped mineral deposits.
- Long term, meaning undiscovered resource potential as viewed from the start of the mineral supply process and including exploration, development, and production phases.

The time dimension is included because selection of appropriate geologic assessment and economic analysis methods depends on the stage of mineral development.

SELECTED PUBLIC POLICY ISSUES

The following policy concerns, grouped into our three geographic units, have been identified.

Broad level includes:

- Competitive position in international markets.
- Domestic supply potential.
- Role of mining in economic development.
- International trade.
- Security of supply.
- Technology transfer.
- Taxation.
- Environmental concerns.
- Research and development.
- Geological surveys.
- Mineral leasing policy.

Broad policy concerns are applicable to national and regional levels only. However, in some cases, the required analysis may be international in scope. (There was a prevailing view within the group that the broad issues are not very important, at least at present, in the United States.)

Area level includes:

- Designation of parks, forest lands, wilderness areas, and wildlife refuges.
- Transportation infrastructure.
- Mineral-processing facilities.
- Land exchanges.
- Native land claims.
- Sustaining local mineral and economic activities such as mining communities.

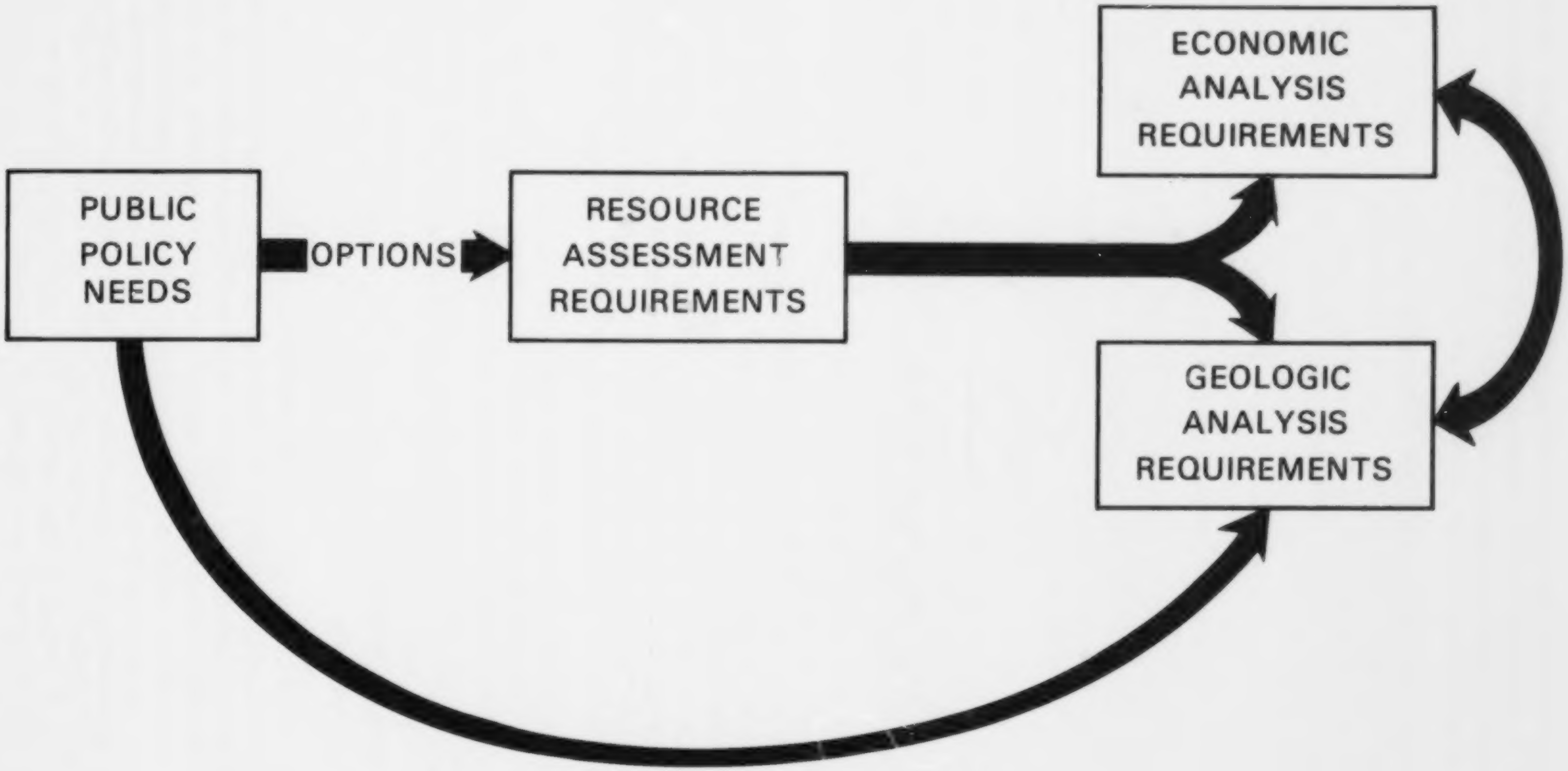
PUBLIC
POLICY
NEEDS
OPTIONS
RESOURCE
ASSESSMENT
REQUIREMENTS
ECONOMIC
ANALYSIS
REQUIREMENTS
GEOLOGIC
ANALYSIS
REQUIREMENTS

FIGURE 2.—Discussion framework.

Issues related to the management of public lands (parks, forests, wilderness areas, wildlife refuges, and lands having Federal mineral rights) were singled out in our discussion as being of prime relevance.

Deposit level includes:

- oInfrastructure support for new mine development.
- oEnvironmental impact approvals.
- oBailouts for operating mines.
- oCompany-government joint-venture and ad hoc negotiated agreements.
- oPublic sector mineral leasing.

ECONOMIC ANALYSIS REQUIREMENTS

The economic methods that would be required to provide analytical support for the range of policy issues identified and some of the general questions that they address are discussed below.

Broad Level

International breakeven cost comparisons can be done in terms of short-term production costs, medium-term development and production costs, and long-term exploration, development, and production costs. The types of questions that can be addressed by breakeven cost analysis include:

- oHow do actual and potential domestic mineral producers rank in league with other major producers worldwide?
- oWhat are the effects of government policies on competitive standing?
- oWhat are the effects of market price movements on the economic viability of the domestic mining sector?

The economic value of a mineral supply process that uses a discounted cash-flow analysis applied to appropriate timeframe estimates and includes expected value, sensitivity and risk analyses techniques, and intangible considerations can be determined. The evaluation procedure would consider these factors:

- oInitial assessment of potential value to society.
- oImposition of government policy alternatives.
- oDetermination of direct effects of policy alternatives in terms of various criteria of desirability.
- oEconomic efficiency (actual value versus potential value).
- oCorporate investment incentive.
- oNet government revenues.

Area Level

An economic analysis method appropriate to the area level would be chosen on the basis of both the policy need and the mineral resource information constraints.

Measures of relative favorability among different resources within a particular area or in terms of mineral resource potential among different areas can be made. These measures would be applicable to most long-term appraisals of undiscovered potential. The two possible approaches are qualitative subjective judgement and quantitative value proxies such as metal content or gross dollar value

Economic value measures can be used for long-term appraisals in special cases, depending on the size of an area and the deposit type (that is, on the possible number of deposits). The evaluation techniques are the same as those used on the broad level and are based on the estimated distribution of characteristics for number of deposits, deposit size, and deposit grade. Economic value measures can also be applied to all short- and medium-term deposit situations by using economic evaluation techniques similar to those used on the broad level.

In view of the difficulties associated with the application and use of relative favorability assessments, discussion focused on ways of making these issues more amenable to quantitative economic analysis. Our group expressed the view that this type of economic appraisal requires a sufficient number of possible deposits (a function of the size of an area, deposit type, and geologic favorability) and similar geologic conditions in both study and control areas. Thus, the area to be examined needs to be of sufficiently size and defined in a geologically consistent manner, so that a meaningful economic assessment can be made, even though the geographic boundaries nominally established for the policy issue at hand may not match up with the assessment area.

Discussion also focused on decisions concerning disposition of public lands at the area level. Frequently, the value of possible land uses, such as forest products or sports, is measured in terms of gross or net dollars. The group expressed the view that mineral resources should be measured similarly. The important point is that each possible alternative use should be compared by the same yardstick.

Deposit Level

Here we are dealing with known deposits. Therefore, these situations are of either a short- or a medium-term nature. The same evaluation techniques used on the broad level are applicable.

RESOURCE ASSESSMENTS

We have attempted (1) to distinguish between different approaches to conducting resource assessments and (2) to indicate economic analysis applications appropriate to specific policy issues according to their time and spatial dimensions. Figure 3 provides an outline of the informational flows. The numbers in parentheses identify the links from geologic resource assessment through economic analysis to policy. These numbers are used in the descriptions that follow, so that each combination can be identified as it is discussed.

In the short and medium term, when the geologic characteristics of deposits are well defined, the discussion group determined that statistical-geostatistical analysis of known deposit characteristics is the most appropriate resource assessment method. This resource assessment method is appropriate for the breakeven cost method of economic analysis at the broad and area levels (1) and for the deposit-specific economic analysis in the short and medium term (2).

For longer term considerations, a variety of resource assessment methods can be used. These methods include four types, all of which are appropriate under some conditions for long-term analysis.

The least comprehensive method uses geologic information and expert judgement to make qualitative assessments of relative favorability at the area level (3). In this case, the resource assessment cannot be extended by economic analysis, because data from the resource assessment stage are insufficient. Hence, the resource assessment alone provides information for policy decisions. This direct linkage back to policy is an example of the economic bypass loop illustrated in figure 2.

A second approach to long-term resource assessment uses statistical analysis and analytical methods to predict aggregate index measures such as metal content and gross dollar values at the area level (4). This method also does not lend itself to economic analysis.

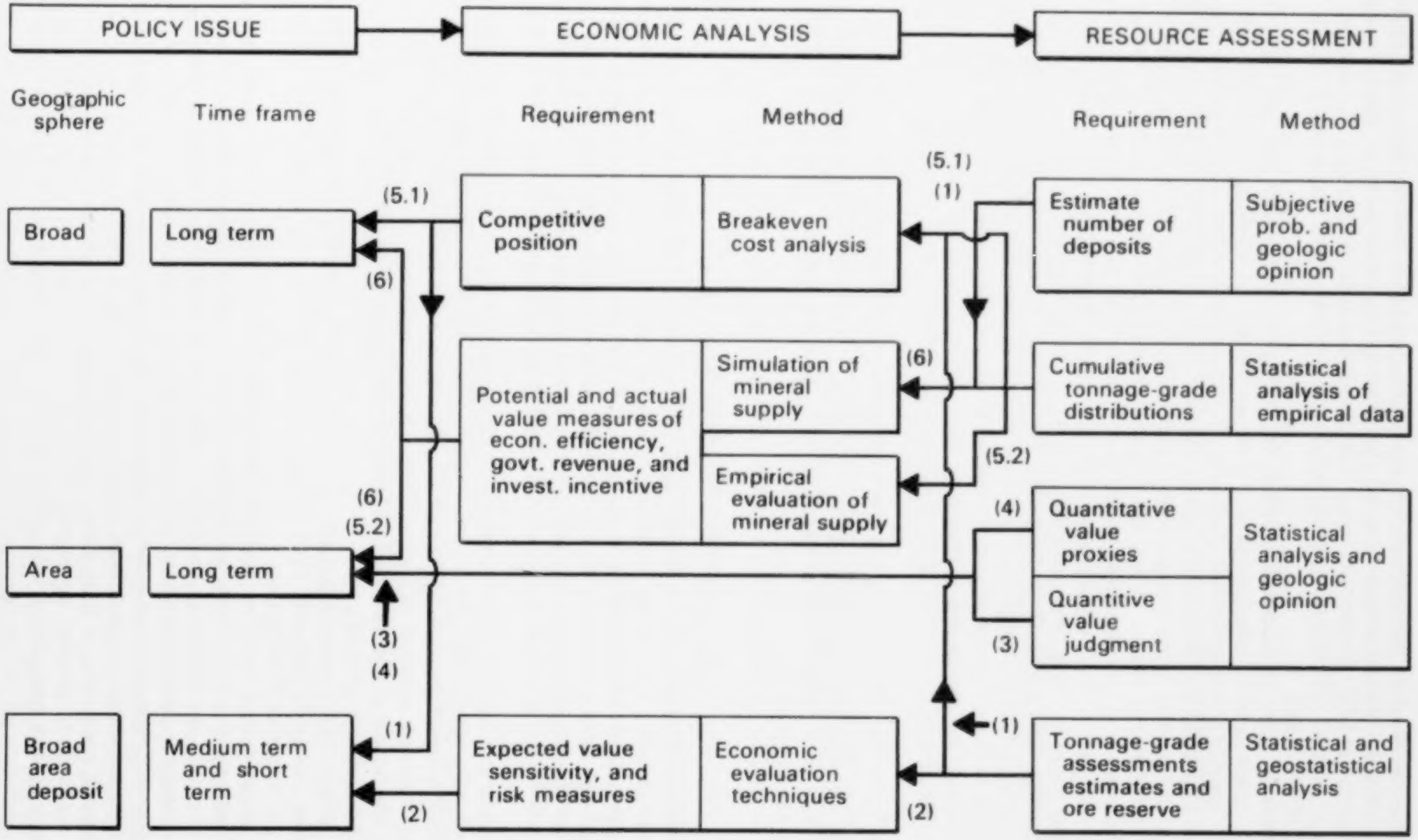
POLICY ISSUE
ECONOMIC ANALYSIS
RESOURCE ASSESSMENT
Geogtaphic sphere
Time frame
Requirement
Method
Requirement
Method
Broad
Long term
Competitive position
Breakeven cost analysis
Estimate number of deposits
Subjective prob. and geologic opinion
Potential and actual value measures of econ. efficiency, govt. revenue, and invest. incentive
Simulation of mineral supply
Empirical evaluation of mineral supply
Cumulative tonnage-grade distributions
Statistical analysis of empirical data
Area
Long term
Quantitative value proxies
Quantitive value judgment
Statistical analysis and geologic opinion
Broad area deposit
Medium term and short term
Expected value sensitivity, and risk measures
Economic evaluation techniques
Tonnage-grade assessments estimates and ore reserve
Statistical and geostatistical analysis
(5.1)
(6)
(6)
(5.2)
(3)
(4)
(1)
(2)
(5.1)
(1)
(6)
(5.2)
(4)
(3)
(1)
(2)

FIGURE 3.—Detailed discussion framework. Paths indicated by numbers in parentheses are discussed in the text.

The third long-term resource assessment method uses cumulative tonnage-grade distributions. This resource assessment methods can provide geologic information for breakeven cost analyses at the broad regional level (5.1). Alternatively, the cumulative tonnage-grade distributions can be used in an empirical assessment of the mineral supply process, which includes the estimation of exploration expenditure and the frequency with which discovered deposits are developed into economic deposits. This combination of resource and economic assessments can support policy analysis at the area level (5.2) (Mackenzie, 1985).

The fourth and most comprehensive long-term resource assessment method uses grade-tonnage cumulative frequency functions (6) (Singer and Mosier, 1983). The grade-tonnage information is combined with subjective estimates of numbers of deposits to estimate mineral occurrence. These results, in turn, are combined with estimates of exploration expenditures. This combination of assessment methods can support policy analysis at the broad region and area levels.

A key factor involved in linking the third and fourth types of resource assessment methods into economic analysis (paths (5.2) and (6)) is the need for realistic simulation of the exploration phase of the mineral supply process. The appraisal must recognize the high-risk nature of mineral exploration, the random component of outcomes, the geologic variability that exists among discoveries, and the influence of the rare but critical "elephant" finds.

EXAMPLE ASSESSMENTS

Although the foregoing discussion provides a useful general framework, our group agreed that what counts most is the ability to carry out the best possible analysis of each specific policy issue as it arises. There is currently a need to assess undiscovered minerals in areas (managed mainly by public authorities) where decisions are being made about access for mineral development and about environmental and scenic values. The state of the art in resource assessment is such that mineral resource values for undiscovered deposits can be made in these areas. Even though such estimates may be very uncertain, the group concluded that studies should be undertaken and procedures scrutinized and altered as we learn more. In this manner, we can hope to improve our estimating abilities. This section reports briefly on two recent resource assessments of undiscovered mineral resources—one in an Alaskan national park and the other in Forest Service wilderness areas in California. Our intention is to show what is possible at present.

In November 1983, an assessment was made of the undiscovered mineral resources of the Kantishna Hills, an area of approximately 200,000 acres within the Denali National Park and Preserve in Alaska (White and others, 1985). The key policy issue was the tradeoff between allowing continued access to the mineral resources and protecting the wildlife and scenic resources present in the area.

To assess the undiscovered mineral potential of the area, a team of 10 experts familiar with the Kantishna Hills was assembled, including geologists and engineers. The assessment process consisted of six basic steps: (1) compilation of the geologic data base for the area; (2) inspection of all existing geologic and engineering data relevant to the formation and production of mineral deposits within the Kantishna Hills area; (3) identification of the types of undiscovered deposits expected to exist within the area; (4) estimation of the geologic, engineering, and economic factors appropriate to each identified deposit type; (5) use of a computer simulation to provide probability distributions for the major outputs of the assessment; and (6) review of the results by the experts.

The major products of the appraisal process included estimates of the area's resource endowment, the proportion of that physical endowment that might be economically recoverable if the area were fully explored, and the gross dollar value of the potentially recoverable commodities within the region. The results of this study and other resource studies of the area were instrumental in the decision by the joint Federal-State Alaska Land Use Council to recommend the expansion of mineral development opportunities in the Kantishna Hills by a locatable mineral-leasing system on unclaimed land in a portion of the study area.

In more recent assessments of other Alaskan areas, the economic analysis methodology has been extended to include a set of generalized mine models and to use a net present value criterion to estimate the portion of the mineral endowment recoverable under various price scenarios. The Kantishna Hills study is an example of resource assessment using quantitative value proxies for undiscovered mineral deposits in a large geographic region (fig. 3, path (4)). Recent extensions of the economic analysis methodology to simulate mineral supply are represented in figure 3 by path (6).

A second example of this type of mineral resource assessment was prepared by a group of 12 scientists from the Branch of Resource Analysis of the U.S. Geological Survey for a collection of Forest Service wilderness tracts in the Pacific Mountain System (Drew and others, 1984). This study was performed by a team of geologists who were familiar with the regional geology and who used the detailed geologic, geochemical, and geophysical data contained in the resource assessment reports for each individual wilderness area as a basis for estimating the undiscovered endowment of the wilderness tracts in the region as a whole. Expert judgments were made by first identifying which types of mineral deposits remain to be discovered on each wilderness tract and then examining the positive evidence for occurrence to estimate the number of undiscoverd deposits occurring. For example, on those wilderness tracts located in Washington State, evidence for the occurrence of 11 porphyry copper systems was found in the maps and descriptions of the geology, geochemistry and geophysics. The team reasoned from these data that 3.5 of those 11 systems were expected to contain porphyry copper deposits similar to those in its data bases describing the grades and tonnages of these types of deposits. A similar analysis was performed for each type of mineral deposit for which some probability of occurrence was judged to exist.

TABLE 1.—Estimates of undiscovered metal endowments of the U.S. Forest Service wilderness tracts in the Pacific Mountain System
(Values in thousands of metric tons)

Metal or oxide	Median undiscovered metal endowment	Confidence level 90 percent	Confidence level 10 percent	Mean endowment	E/C[1] ratio
Chromic oxide	60	40	100	68	0.1
Copper	5,700	850	23,000	10,000	2.6
Gold	.15	.038	.63	.30	1.2
Lead	110	0	1,700	880	.1
Manganese	7.6	0	350	180	.01
Mercury	2.7	.27	20	11	1.3
Molybdenum	220	25	1,100	460	8.5
Nickel	0	0	0	7.0	0
Silver	1.6	.25	9.2	4.5	.4
Tungsten	23	0	400	220	2.0
Zinc	640	89	3,400	1,700	.7

[1] Ratio of median undiscovered metal endowment to average U.S. apparent consumption for the years 1979-82 (U.S. Bureau of Mines, 1984).

A Monte Carlo simulation model was then used to convert the number of each type of mineral deposit expected to occur into a distribution describing the probability that specific volumes of each type of metal occur. The byproduct metals from the polymetallic deposit types were also accounted for in this simulation. Table 1 shows the final summary by metal commodity. This summary presents estimates of the median and mean undiscovered metal endowments along with confidence intervals and ratios of undiscovered metal endowment to consumption. This approach to resource assessment is most like that shown as path (6) in figure 3. However, the assessment provides estimates of tonnage only; economic analysis is not undertaken.

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THE TECHNICAL PERSPECTIVE

USER-FRIENDLY MINERAL DEPOSIT MODELS

By Paul B. Barton, Jr.
U.S. Geological Survey

ABSTRACT

Mineral deposit models provide tools for both mineral exploration and resource assessment. Available models represent a spectrum of understanding ranging from the almost entirely empirical model (for example, for gold veins in metamorphic rocks) to the almost entirely genetic model (for example, for potassium-bearing evaporites). The genetic models are far more powerful because they are much more flexible.

Access to the knowledge residing in the collected models is straightforward for the explorationist, who focuses first on the commodity and then moves directly to the appropriate models. In contrast, the resource assessor must recognize the appropriate models in the context of voluminous (and, insofar as individual mineral deposit types and models are concerned, mostly extraneous) information derived from geologic observations. Extensive and comprehensive cross indexing of attributes provides the necessary key to models for the assessment process.

INTRODUCTION

The body of descriptive and interpretive information concerning mineral deposits is both tremendous and scattered; no single expert, let alone each individual struggling over outcrops, drill logs, or geochemical data, could ever read it all, let alone assimilate it. Nevertheless, that information is the primary means of bringing past experience to bear on new problems of mineral exploration and resource assessment. The natural tendency of mankind to try to understand and find explanations for the things that he observes has led to the lumping of deposits into groups, each of which possesses similar characteristics.

The systematically arranged information that represents a type of deposit constitutes the model for that type. Ideally, a model represents only nonsite-specific features and thus has a general application. One of the most critical tasks in modeling today is distinguishing essential features from incidental accessory features.

The following example illustrates the problem. One of the commonly accepted attributes of the model for carbonate-hosted lead-zinc deposits of the Mississippi Valley type is the presence of secondary dolomite. But do we do know that this attribute is essential? Suppose that a deposit were found in limestone. Would we reject its assignment to the Mississippi Valley class? Or could it be that the critical property is permeability and that the formation of dolomite either (1) enhances permeability (and thereby makes the ground more favorable) or (2) reflects preexisting permeability that is exploited by both the dolomite and the ore? Or does the dolomite perhaps merely record a particular range of Ca/Mg ratio in the fluid, which in turn is characteristic of the basinal brines that constitute the ore fluid? In any event, the dolomite is a powerful ore guide and belongs somewhere in the "final model."

Of course, models are not new. They have been with us for as long as man has thought about mineral deposits. But ancient, and even some not so ancient, models have been incomplete in their descriptive aspects and unreasonably speculative in their genetic interpretations.

In many respects, the science of mineral deposits is following an evolutionary pattern similar to that of the theory of continental drift, which was advocated by a few for almost a century but was rejected by the majority of earth scientists until ocean-bottom topography, magnetic striping in the sea floor, absolute dating of the sea floor, and global seismic patterns enabled the almost universally accepted modern theory of plate tectonics to emerge in the 1960's. In mineral deposits today, a great number of modern tools--such as geochemistry, stable isotopes, absolute age dating, geophysics of all sorts, numerical process modeling, fluid inclusions, and many others--have provided ways to identify the "correct" interpretations amid a host of possible alternatives. Today's knowledge is uneven and imperfect in many regards, but it is evolving rapidly and has clearly progressed from an occult medieval art to a modern science that shows great promise of addressing real societal problems concerning resource assessment.

The model provides a mechanism to let the most knowledgeable persons communicate their information to the rest of us in a very compact form, without having to use an entire library.

MODEL SUBTYPES

Figure 1 shows the evolution of model subtypes. The basic ingredients for mineral deposit models are the descriptions of individual deposits. As groups of deposits are recognized to possess similar features, the attributes of the group become the descriptive model. Deposits that do not possess the same attributes as those selected for the deposit type are diverted into other model classes.

The group of deposits as a whole possesses some statistical attributes regarding the probability that any individual may be of a certain size or grade; these properties are represented by grade-tonnage models. As the reasons for the attributes become understood, the genetic model evolves from the descriptive.

When the model has become genetic, two additional model subtypes become possible:

1. Several quantitative process models can apply to the same deposit model. For example, we might model the cooling rate for a pluton, the heat and geochemical budgets and hydrologic trajectories of water set in motion by the heat engine that the pluton represents, the distribution and quantities of minerals deposited in the fractures around the pluton, and so on. Most of these process models are imported into economic geology from related geologic disciplines such as geochemistry, petrology, geothermal studies, and so on. We have far to go in acquiring all the quantitative process models of use to us, but the ability to acquire them is certainly within our grasp.
2. The last subtype shown in figure 1, the probability-of-occurrence model, is thusfar only a primitive device, whose final form (and, indeed, whose feasibility as a valid tool) remains obscure to this observer. Various models, however, have been applied to estimating the magnitude of undiscovered resources, as later authors will describe. Here, we try to estimate the probability that a given type of deposit will be associated with a given area having a given set of geologic constraints. Such an estimation may appear as only a wishful dream, but we might recall that petroleum geologists already can make reasonable estimates about the amount of petroleum that might be found in a basin, provided that they know enough about the sedimentary fill and its postdepositional history.

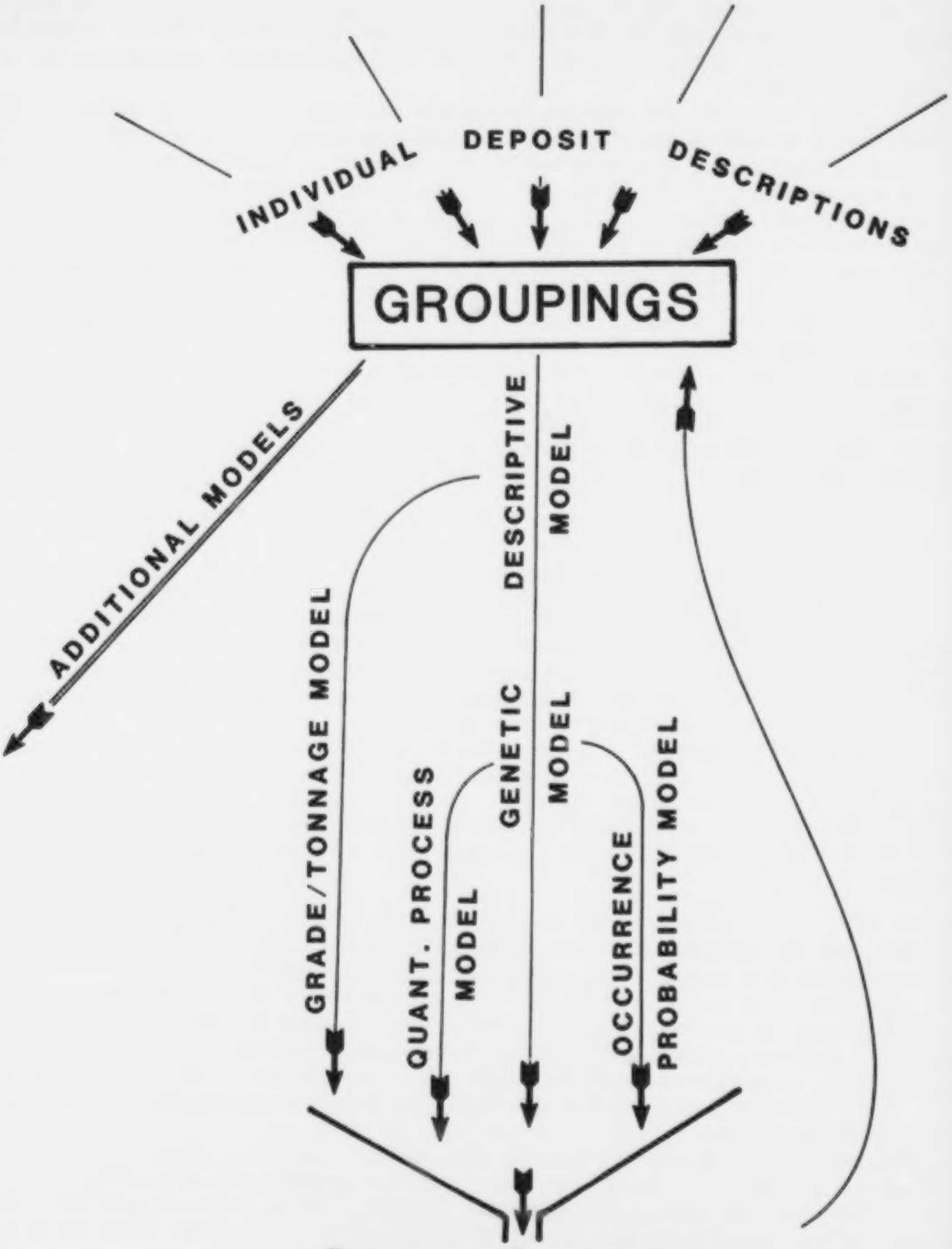
INDIVIDUAL DEPOSIT DESCRIPTIONS
GROUPINGS
ADDITIONAL MODELS
DESCRIPTIVE MODEL
GRADE/TONNAGE MODEL
GENETIC MODEL
QUANT. PROCESS MODEL
OCCURRENCE PROBABILITY MODEL
"FINAL" MODEL

FIGURE 1.—Evolution of model types. It is essential that such a conceptual structure represent the repetitive cycling of information leading to continual refinement of the groupings of deposits that represent each model type.

Extending this philosophy to "hard-rock" deposits, for example, we might ask how many podiform chromite deposits one would expect to find per cubic kilometer of tectonized harzburgite within an ophiolite complex. Or we might make the question even harder and more useful by asking, "How many podiform deposits can be expected to be larger than one hundred thousand tons, and can we afford to search for them?" These questions are hard to answer, even for deposit types about which we know a great deal, but he answers would be invaluable to national and corporate policymakers and planners as they seek to reach decisions concerning economic or development policies.

All of these subtypes are combined to form the "final model," which is never really "final" because improvements will continue to be made. Each improvement recycles back through the intellectual edifice to help refine each of the other components.

Figure 2 shows qualitatively the relative ways in which the various subtypes are used. Note that each subtype has its use and that no one subtype is entirely sufficient for the explorationist, the economic or land use policymaker, the educator, or the scientist. Further, regardless of how focused our needs may be, no one model subtype is a stand-alone item.

UNDERSTANDING MINERAL DEPOSITS

Figure 3 is a schematic view of some of the various ways in which our understanding of mineral deposits may change with time, progressing asymptotically toward the ideal "10" rating. One example of a nearly complete model might be the gold-bearing placers, which are relatively simple to understand. The problems of placer exploration and exploitation are concerned more with site-specific local factors than with inadequacies of the model.

At the other extreme, the huge silver-lead-zinc veins of the Coeur d'Alene district remain enigmatic despite much study. Our understanding of other deposit types has progressed irregularly. Advances in phosphorite came as the deposits were recognized first as chemical precipitates, then as the product of upwelling, and now as the localization of upwelling in certain positions relative to currents, winds, and global plate configurations.

Similarly, knowledge of Mississippi Valley ores improved successively as fluid inclusions showed the depositing fluids to be warm brines and thereby proved that the deposits could not be the product of meteoric waters or unmodified seawater. The model advanced further when the sites of deposition were shown to be associated with paleoaquifers and again when mineralogic and geochemical studies showed the aquifers to be regional in extent. Nevertheless, even now, we have much to learn about this very important deposit type.

If we rank several classes of ore deposits on a normalized "learning curve," we can create a trend like the one in figure 4. Our knowledge base is unequal for different types of deposits and this diagram schematically illustrates (by using a ratio as the horizontal coordinate) the relative levels of understanding for some important types. Some types are fairly well understood, whereas others are so poorly understood that they defy attempts to find sibling deposits.

It is important to realize that merely having a "complete" model does not guarantee that we can find all such deposits, because some important features may be very difficult to understand. Kimberlite pipes, for example, would probably rank well up on our scale of relative understanding, but what causes a particular pipe to be diamond bearing is very enigmatic. Even more difficult would be to predict where pipes might be found, for one could argue that almost any terrane is permissively prospective for diamond pipes; even the most enthusiastic prospector, however, would probably admit that the middle of the Greenland icecap would be a poor bet.

Level of Use:

Major X

Minor X

Minimal x

USES	GRADE/TONNAGE	DESCRIPTIVE	GENETIC	PROBABILITY OF OCCURRENCE	QUANTITATIVE PROCESS
	SUBTYPES OF MODELS				
EXPLORATION/DEVELOPMENT	X	X	X	X	X
SUPPLY POTENTIAL	X	x	x	X	x
LAND USE	X	X	x	X	x
EDUCATION	x	X	X	X	X
RESEARCH GUIDANCE	X	X	X	X	X

FIGURE 2.—Application of the five model subtypes by various users.

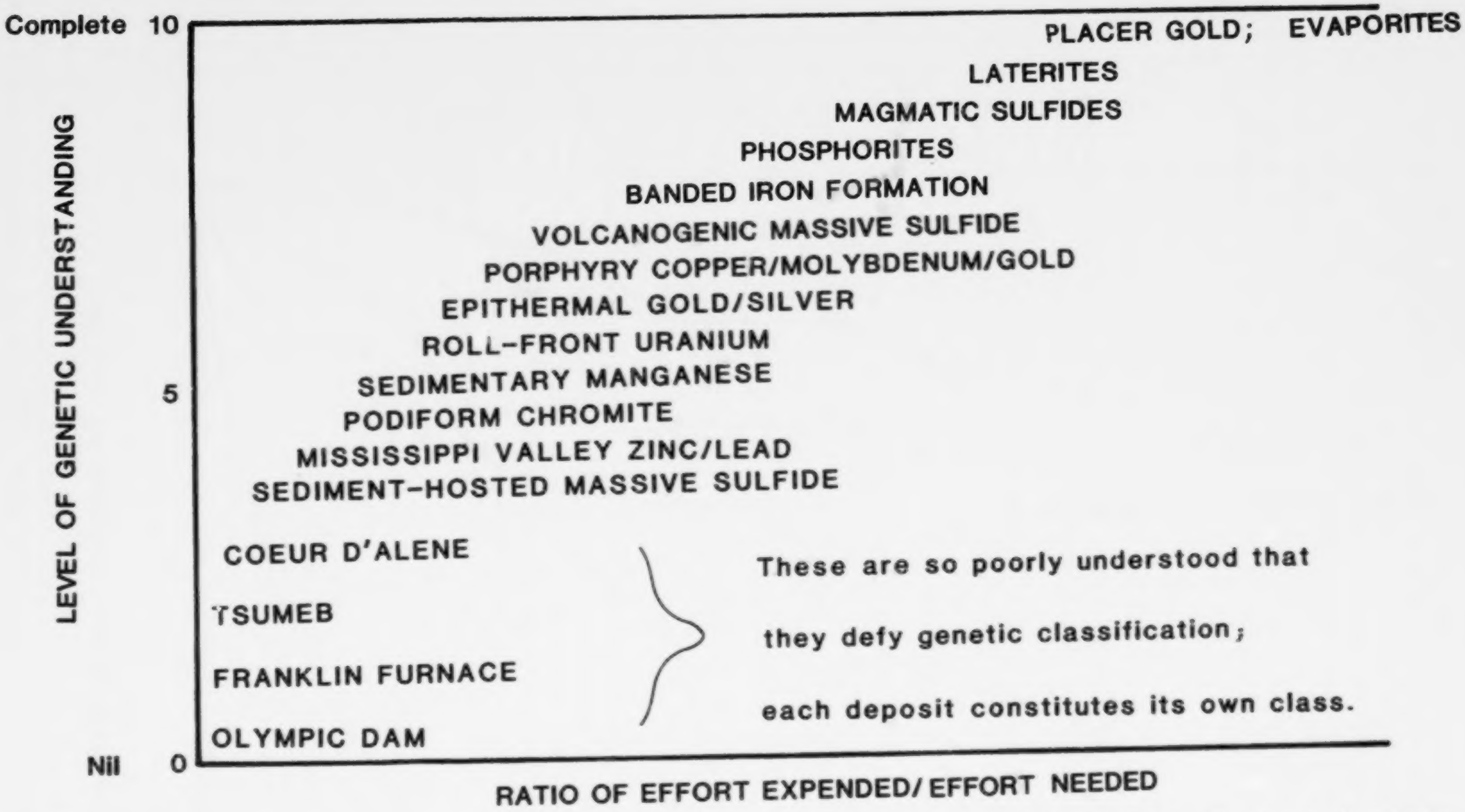

FIGURE 3.—Schematic growth patterns for the understanding of some typical genetic models. The level of genetic understanding ranges from 0 (nil) to 10 (complete).

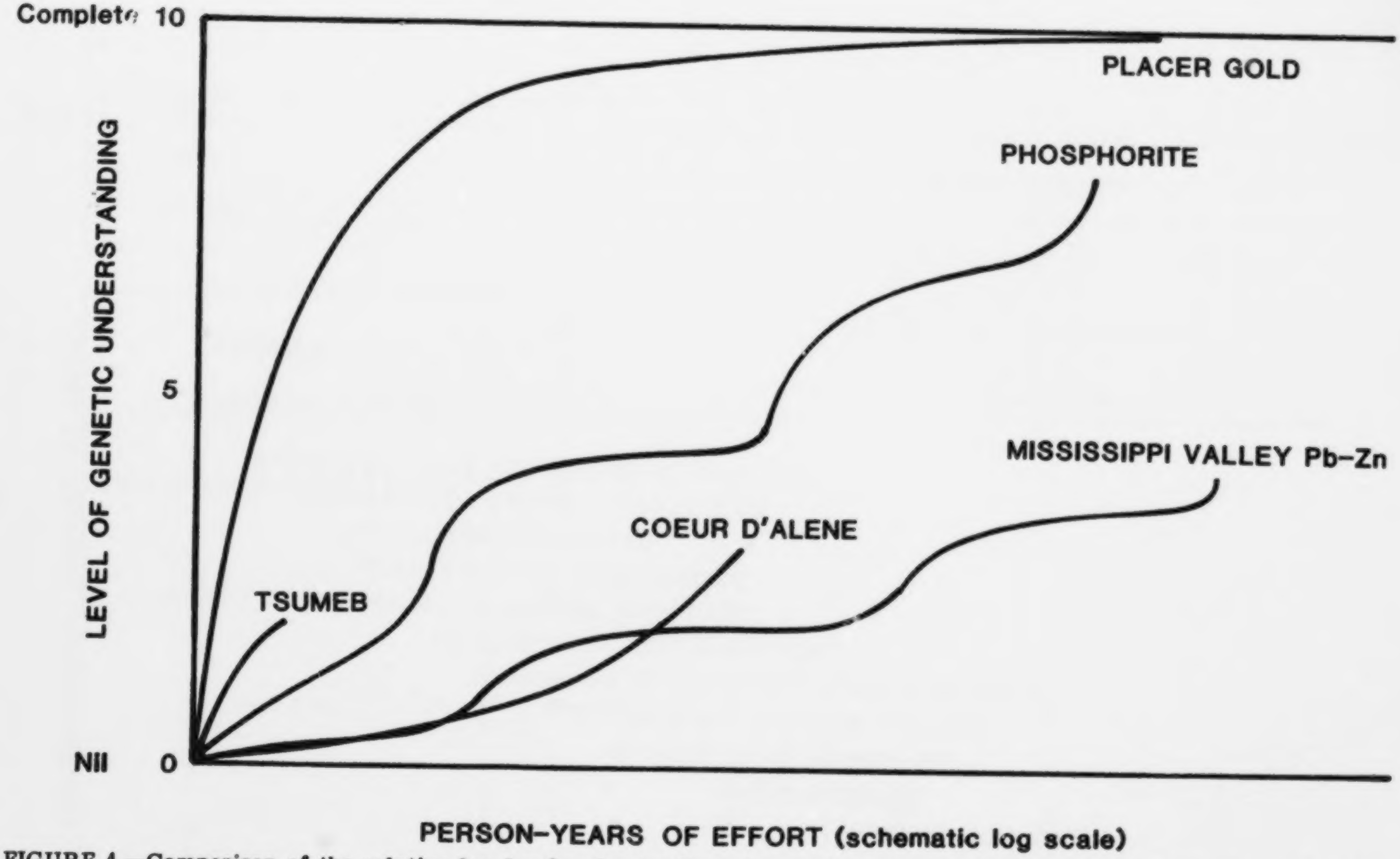

FIGURE 4.—Comparison of the relative levels of understanding of some important model types. The vertical coordinate is the same as that in figure 3, but, because the magnitude and difficulty of acquiring the genetic information differ so widely among model types, the horizontal coordinate is "normalized" by plotting a hypothetical ratio (amount of work already done divided by the amount of work needed to acquire a complete (10) understanding). There is no pretense of mathematical rigor for this plot; in fact, since the ideal 10 score would be approached only asymptotically, the ratio plotted would actually be indeterminant. Nevertheless, the concept of ranking level of understanding in terms of the difficulty in acquiring that understanding is a useful one.

If we were to place fuels on figure 4, coal would probably rank up with placers and evaporites. Petroleum would be not far behind, perhaps getting an 8 or 9 on this scale.

The mention of coal and oil brings up another point that nontechnical persons seldom appreciate. The total number of comparable models for oil, gas, and coal probably could be counted on the fingers of two hands; despite their immense economic importance, they are represented by a small set of model types. In contrast, we probably have a hundred or so model types for nonfuel minerals. Thus, it is no surprise that we have far to go to lift the level of understanding for nonfuel deposits up to that enjoyed by the fossil fuels.

EXAMPLE OF A TYPICAL MODEL

Now let us consider briefly, as a typical model, the model of volcanogenic massive sulfides." This example is my own revised and expanded format, taken from one used by Dennis Cox and Donald Singer.

Figure 5 gives general information and summarizes the regional geologic features with which this deposit type is associated. Figure 6 lists the local geologic attributes, and figure 7 presents some of the aspects that the class as a whole possesses. An idealized cross section through the volcanogenic massive sulfide summarizes the spatial relationships (fig. 8).

Cox and Singer have compiled about 90 brief models from a worldwide sampling of ore deposits and are preparing them for publication as a U.S. Geological Survey Bulletin. Roger Eckstrand's excellent summary published by the Canadian Geological Survey (Eckstrand, 1984) has about 40 models, but it represents only major Canadian deposits. Although the formats differ, the contents and philosophies of the two summaries are similar.

The models themselves constitute a substantial mass of information, but that information may not be as accessible as we would wish. To illustrate what I mean, let us compare the needs of the explorationist with those of someone who is studying the geology of a specific area.

A typical operational sequence (fig. 9, top) for exploration begins with a policy decision by management to concentrate on a particular commodity (for example, gold or barite). One moves directly to the models and selects the one or two that are most promising. Then, a region possessing the appropriate regional characteristics is chosen, and field studies are initiated to find the local attributes most indicative of mineralization. If this phase is successful, it leads to the identification of a target for detailed mapping, sampling, or drilling.

But a geologist studying a specific area has a different sort of agenda, as figure 9 (bottom) also shows. He starts with field observations that might apply to any one or several of perhaps a hundred possible types of deposits. This problem recurs many times for the U.S. Geological Survey in evaluating areas for their suitability for alternative types of land use. A geologist may be an expert in half a dozen of these hundred deposit types, but he certainly cannot be an expert in all of them. Therefore, we need to present the information from the models in a format that will help him move from field observations to the selection of models appropriate for the terrane that he is examining. We would also like to suggest to him some additional observations or tests that he might make to let him do the best study for the least cost.

Our approach to making this package more user friendly is to generate long lists of attributes that constitute an exhaustive cross index of all of the attributes noted in the models. A partial table of contents of the attributes index is shown in figure 10.

We also need some sort of rating scheme to indicate just how common some features may be. The scheme that we use is shown in figure 11. The higher the number, the more common the feature. In our present compilations, the numbers are assigned as

BRIEF MODEL DESCRIPTION

DEPOSIT TYPE, Subtype:
Volcanogenic massive sulfide

Number:

OTHER NAMES FOR SAME TYPE:
Kuroko- or Noranda-massive sulfide

COMPILED BY:
Donald Singer

DATE:
Dec. 1982

REVISED BY:
P. Barton

DATE:
Sept. 18, 1984

PRINCIPAL COMMODITIES PRODUCED:
Cu, Zn, rarely S

BYPRODUCTS:
Pb, Ag, Au

EXAMPLES OF TYPICAL DEPOSITS:
Noranda, Que.; Kuroko, Japan; Jerome, AZ; Kidd Creek, Ont.; Rio Tinto, Spain; Boliden, Sweden.

RELATIVE IMPORTANCE OF THIS TYPE OF DEPOSIT:
World class Zn, Cu, Ag; important Au, Pb; minor S

DESCRIPTIVE/GENETIC SYNOPSIS:
Submarine silicic plutons heat and circulate seawater; acidity and metals are derived as product of rock-water interaction sulfides are deposited in stockworks and above seafloor vents. Post-ore fluids alter the hanging wall. Most, but not all, deposits are buried deeply and metamorphosed after mineralization.

ASSOCIATED OR RELATED DEPOSIT TYPES:
Gold-qtz. veins; bedded barite; gypsum/anhydrite in volcanics; oxide facies iron fm.

GENERAL REFERENCES:
Franklin et al, 1981; Ohmoto and Skinner, 1983.

REGIONAL GEOLOGIC ATTRIBUTES

TECTONOSTRATIGRAPHIC SETTING:
Island arc, often as magmatism shifts from mafic to felsic.

REGIONAL DEPOSITIONAL ENVIRONMENT:
Back arc rifting; deep, poorly oxygenated, marine water; felsic submarine volcanism.

AGE RANGE:
Archean through Cenozoic.

FIGURE 5.—General information and summary of regional geologic features of volcanogenic massive sulfide model. Based on unpublished 1982 compilation by Donald Singer.

much by guess as by knowledge, but statistical quantification is just a matter of time. As a first example, figure 12 presents a part of the Commodities and Geochemistry index showing a few of the deposits in which gold is found as a principle commodity, as a byproduct, or as a geochemical anomaly. In the case of the Cu-Au porphyries and the Cyprus massive sulfides, the choice between principal and byproducts is sometimes interchangeable. The geochemical signature for gold in the Keewenaw copper deposits is

LOCAL GEOLOGIC ATTRIBUTES

HOST ROCKS:
Felsic and mafic submarine volcanics and associated sediments.

ASSOCIATED ROCKS:
See "host rocks". Ore is often associated with shale, especially carbonaceous shale. Carbonate and fluvatile rocks rare.

MINERALOGY:
Feeder-vein zone of pyrite + chalcopyrite +/- sphalerite + pyrrhotite; lower mass. sulfide of pyrite + chalcopyrite +/- pyrrhotite; upper massive zone of sphalerite +/- galena, tetrahedrite, and barite. Quartz, chlorite; +/- anhydrite, barite, hematite, magnetite. Gahnite and ferromagnesian silicates are common in metamorphosed ores.

STRUCTURAL SETTING:
Submarine topographic lows in lava dome complexes; ore bodies are often slumped; growth faults are common.

WALLROCK ALTERATION:
Chlorite + albite below mineralization; silica + chlorite + sericite in feeder zone; zeolite + montmorillionite + chlorite above ore (alteration of hanging wall is common).

EFFECT OF WEATHERING:
Strong gossan development, enrichment in Au, Ag, Cu.

EFFECT OF METAMORPHISM:
Mechanical disruption of ore; extensive recrystallization; characteristic development of gahnite at amphibolite grade.

GEOCHEMICAL SIGNATURES:
Gossan has Pb, Au; Na depleted and Mg and Zn enriched in wallrock; ores have Cu, Zn, Fe, Pb, As, Ag, Au, Sb, Ba, Se, Bi, Sn. Economic Pb only where basement is continental.

ISOTOPIC SIGNATURES:
O lightened in altered rocks, H heavier than unmodified sea water; S varies widely; Pb matches growth curve.

FLUID INCLUSIONS:
Salinity near sea water, daughter minerals absent; temperatures 200-350°C. Inclusions distinguish feeder veins from those in porphyry systems.

GEOPHYSICAL SIGNATURES:
Ores are good electrical conductors and are significantly denser than the wallrocks; pyrrhotite and/or magnetite bodies are strongly magnetic; oxidizing bodies may stunt or otherwise modify vegetation.

FIGURE 6.—Local geologic attributes of volcanogenic massive sulfide model.

negative, which means depletion rather than enrichment. Figure 13 shows an example from the Ore Controls index showing some of the deposits for which the presence of organic matter is significant and also a few of the deposits associated with paleoaquifer systems. At present, we have quite a few pages of such cross indices, and the list steadily grows longer.

ORE CONTROLS/EXPLORATION GUIDES:

Deep-water marine sedimentation, association with submarine volcanism, particularly when mafic volcanism shifts to felsic. Lava domes and local submarine fanglomerates mark the growth faults that localize mineralization. Widespread, thin, cherty strata, +/- iron minerals, mark exhalative events. Gahnite ($ZnAl_2O_4$) in stream sediments. Several ore bodies often occur at the same stratigraphic level in clusters 2 or 3 km across.

MODEL-CLASS ATTRIBUTES

GRADE-TONNAGE CHARACTERISTICS:

		432 deposits	
	upper decile	median	lower decile
millions of tonnes	19	1.6	0.13
grade Cu %	3.5	1.3	0.4
Zn %	9.0	2.0	
Pb %	1.9		
Au g/t	2.3	0.13	
Ag g/t	98	11	

PROBABILITY-OF-OCCURRENCE CHARACTERISTICS:

(not available)

APPLICIABLE PROCESS MODELS (References):

Cathles, 1983, Econ. Geol. Monograph 5;
Ohmoto and Skinner, 1983, Econ. Geol. Monograph 5

ESTIMATED LEVEL OF GENETIC UNDERSTANDING (On scale of 0 to 10):

_7_

SIGNIFICANT UNANSWERED QUESTIONS:

Why are not all sub-seafloor volcanic systems mineralized? What is the relation of these ores to the Besshi-type deposits and the sediment-hosted massive sulfides? How significant is the role of magmatic fluids relative to that of sea water?

SPECULATIONS ABOUT ANSWERS TO SIGNIFICANT QUESTIONS:

A critical balance of water input relative to heat input is required, otherwise there is either quenching of the intrusive or a submarine phreatic eruption. The other seafloor massive sulfides are derived either from Mid-ocean-ridge-type basaltic systems, Red Sea-type hot brine pools, and/or from cool, exhalative Mississippi Valley-type fluids. The redox state of the sea bottom is critical to the preservation of the sulfides prior to burial.

FIGURE 7.—Attributes of the class to which the volcanogenic massive sulfide model belongs.

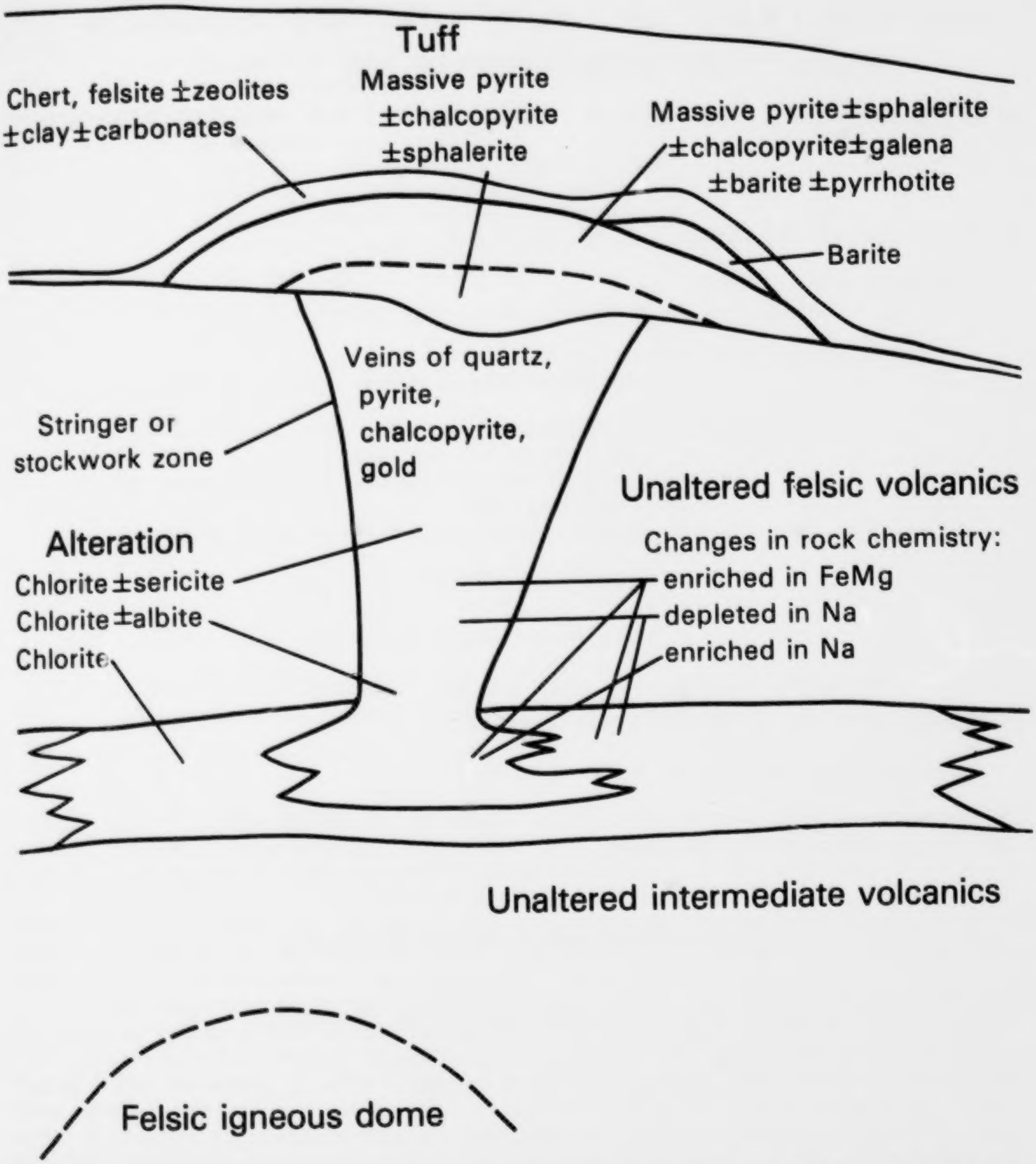
Tuff
Chert, felsite ±zeolites ±clay±carbonates
Massive pyrite ±chalcopyrite ±sphalerite
Massive pyrite±sphalerite ±chalcopyrite±galena ±barite ±pyrrhotite
Barite
Veins of quartz, pyrite, chalcopyrite, gold
Stringer or stockwork zone
Unaltered felsic volcanics
Alteration
Chlorite±sericite
Chlorite±albite
Chlorite
Changes in rock chemistry:
enriched in FeMg
depleted in Na
enriched in Na
Unaltered intermediate volcanics
Felsic igneous dome

FIGURE 8.—Schematic cross section of volcanogenic massive sulfides. The massive sulfide bodies are from a few tens to a few hundreds of meters in horizontal dimension (Donald Singer, personal communication, 1985).

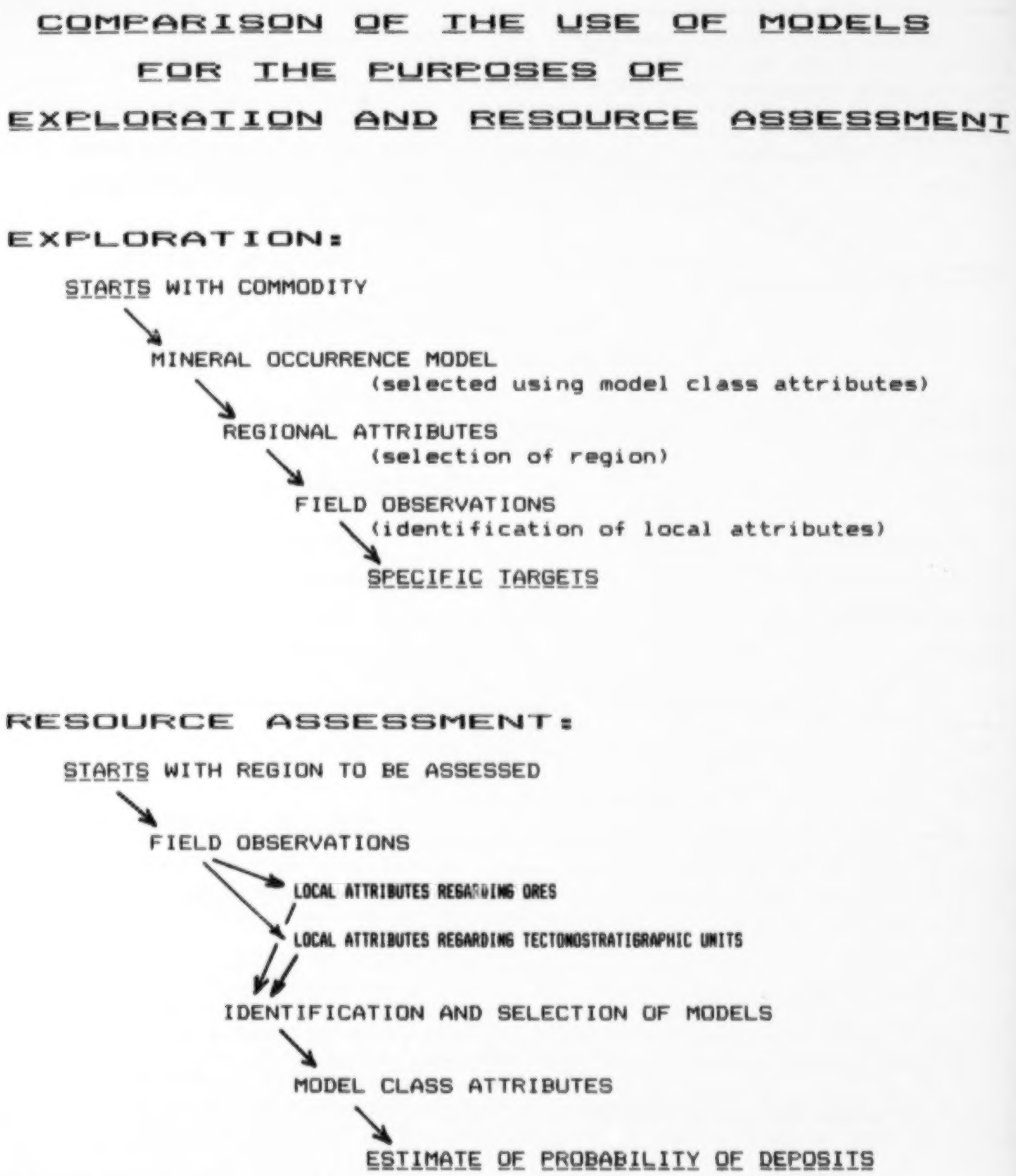
COMPARISON OF THE USE OF MODELS
FOR THE PURPOSES OF
EXPLORATION AND RESOURCE ASSESSMENT
EXPLORATION:
STARTS WITH COMMODITY
MINERAL OCCURRENCE MODEL
(selected using model class attributes)
REGIONAL ATTRIBUTES
(selection of region)
FIELD OBSERVATIONS
(identification of local attributes)
SPECIFIC TARGETS
RESOURCE ASSESSMENT:
STARTS WITH REGION TO BE ASSESSED
FIELD OBSERVATIONS
LOCAL ATTRIBUTES REGARDING ORES
LOCAL ATTRIBUTES REGARDING TECTONOSTRATIGRAPHIC UNITS
IDENTIFICATION AND SELECTION OF MODELS
MODEL CLASS ATTRIBUTES
ESTIMATE OF PROBABILITY OF DEPOSITS

FIGURE 9.--Comparison of the use of models for exploration and for resource assessment.

But even this matrix of models and attributes does not cover all our needs, because there are geologic interrelations that need to be developed more fully than our simple index can do. Let us use the early Mesozoic basins of eastern North America as an example. Late Triassic plate reconstruction shows the matched rift basins in North America and Africa constituting the incipient stages in the formation of the Atlantic

ATTRIBUTES INDEXED:

PRINCIPAL AND BY-PRODUCT COMMODITIES
GEOCHEMISTRY
MINERALOGY
WALLROCK ALTERATION
HOST AND ASSOCIATED ROCK TYPES
REGIONAL LITHOTECTONIC FEATURES
ORE CONTROLS (METALLOTECTS)
WEATHERING AND RESIDUAL HEAVY MINERALS
ORE AND HOST TEXTURES

FIGURE 10.—Partial table of contents of attributes indexed.

EXPLANATION OF NUMERICAL RATINGS:

THE NUMBERS ARE ESTIMATES OF THE PERCENTAGE OF

DEPOSITS OF A GIVEN TYPE THAT POSSESS THE ATTRIBUTE.

1 = 0-10%; 2 = 10-30%; 3 = 30-70%

4 = 70-90%; AND 5 = 90-100%

FIGURE 11.—Chart showing the basis for assigning numerical values to frequency of occurrence within model types.

Ocean. The rift basins constitute a geologic environment that we shall now consider in terms of potential mineral deposits. What kinds might there be? What should the geologist studying these basins be sure to consider?

Figure 14 illustrates five types of deposits associated with this environment: rift-related barite deposits, iron skarns of the Cornwall type, sandstone uranium deposits, stratiform syngenetic sedimentary silver and base-metal sulfides, and Noril'sk-type nickel ores. Let us examine the last type more closely.

These magmatic nickel deposits are products of the separation of nickel-, copper- and platinum-group metals as an immiscible iron sulfide melt whenever crustal sulfur from either evaporitic sulfate or sedimentary pyrite contaminates the primitive mafic magma. The detection of such a deposit might well involve the consideration of the trace-element chemistry of the basalts, the selection of areas where sedimentary sulfur occurs in proximity to basaltic sills, or the screening of sulfur isotopes to identify which intrusions have had their magmatic sulfur signatures modified by the assimilation of sedimentary sulfur. Without the models in mind, a geologist studying the Triassic basins might well not even think about the possibilities for Noril'sk-type deposits.

Although some of the papers that follow will provide additional examples of suitable interpretations, I believe that we have only just begun to grapple with the regional geologic environments, especially where multiple processes have been operative. As an example, how should one specify the essential regional geologic attributes for the Arizona porphyry copper deposits that are made economic (or were economic at one time) by (1) Tertiary enrichment of (2) Laramide porphyry-hydrothermal systems that intruded (3) cratonal sediments overlying (4) a metamorphosed and intruded

SAMPLE OF COMMODITY/GEOCHEMISTRY FILE

Commodity	Principal Product	By-product	Geochemical Anomaly	Deposit Type
Au		2	3	komatiitic Ni-Cu
	5		5	Au-quartz veins, low sulfide
		4	5(dist.)	porphyry Cu, general
		3	4	porphyry Cu, skarn-related
		4	4	Cu skarn
		4	4	Zn-Pb skarn
	4 <>	5	5(prox.)	porphyry Cu-Au
		3	5(dist.)	porphyry Cu-Mo
		3	4	Fe skarn
	1	3	4	polymetallic replacement
			4	replacement Mn
		3	4	Sn-polymetallic veins
			4(dist.)	porphyry Mo-low F
		4	4	volcanic-hosted Cu-As-Sb
	5		5	Au-Ag-Te veins
			(-3)	basaltic Cu
	4 <>	4	5	Cyprus massive sulfide
	1	3	4	Besshi massive sulfide
		2	3	Blackbird Co-Cu
	4	2	5	hot spring Au-Ag

* (dist.) and (prox.) indicate respectively distal and proximal zoning positions. The <> symbol indicates that the Principal Product and By-product designations may switch.

FIGURE 12.—Part of the index for Commodities and Geochemistry. The entire list for this category is about 20 times longer.

Proterozoic island arc complex, and the whole area was superjacent to (5) a late Mesozoic subduction zone? Are only (1), (2) and (5) important? Why? Why not? Regardless of the complexities that an ambiguous Nature imposes on us, we must move toward dealing effectively with the regional geologic setting, because such large-scale features are the most prominent ore controls and represent the only statistically significant basis on which to construct probability-of-occurrence models.

SUMMARY

Consideration of mineral deposit models before and during geologic studies (not just at the end) may play a significant role in improving the efficiency as well as the quality of those studies. The less well known the geology, the more important it is to have some guidelines, and models help provide those guidelines.

SAMPLE FROM ORE CONTROLS FILE

Ore Control	Frequency	Deposit Type
Lava domes	4	volc. massive sulfide
	3	volc. Au
Organic matter	4	sandstone U
	4	shale-hosted Zn-Pb
	3	carbonate Pb-Zn
	4	red/green-bed Cu
Paleoaquifers		All deposits in veins are occupying former aquifer structures.
	5	dolomitic Cu-Co
	5	sandstone U
	5	carbonate Pb-Zn
Pillow basalts	5	Cyprus massive sulfide
	3	volc. massive sulfide
Redox interfaces		Supergene enrichment occurs at the water table, a redox interface.
	5	dolomitic Cu-Co
	5	sandstone U
	5	sedimentary Mn
Reduced horizons in redbed sequence	5	dolomitic Cu-Co
	5	red/green-bed Cu
	5	sandstone U
in marine sediments	5	shale-hosted Zn-Pb
	4	volc. massive sulfides
Roll fronts	3	sandstone U
Sheeted dikes, basalt	3	Cyprus massive sulfide
	3	podiform Cr

FIGURE 13.—Part of the index for Ore Controls.

In closing, let us reemphasize that mineral deposit models represent the digestion of a great mass of geologic information. They provide a medium with which to communicate that information to the scientific and technical communities as well as to the economic, educational, and political sectors of society, and they offer promise of the optimum identification of mineral resources.

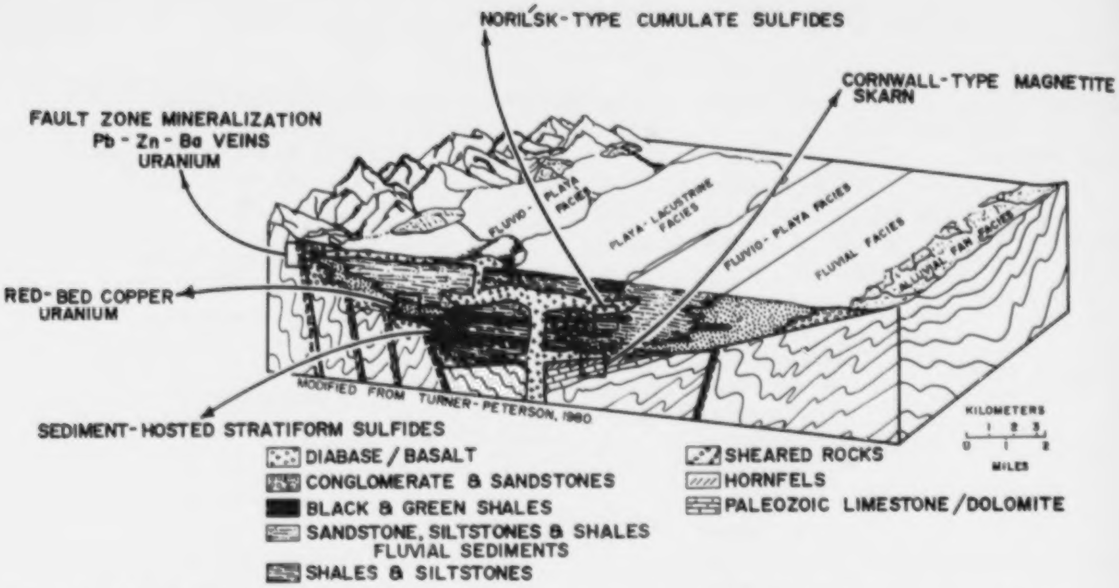
NORIL'SK-TYPE CUMULATE SULFIDES
CORNWALL-TYPE MAGNETITE SKARN
FAULT ZONE MINERALIZATION
Pb - Zn - Ba VEINS
URANIUM
FLUVIO-PLAYA FACIES
PLAYA-LACUSTRINE FACIES
FLUVIO-PLAYA FACIES
FLUVIAL FACIES
ALLUVIAL FAN FACIES
RED-BED COPPER
URANIUM
MODIFIED FROM TURNER-PETERSON, 1980
SEDIMENT-HOSTED STRATIFORM SULFIDES
KILOMETERS
0 1 2 3
0 1 2
MILES
DIABASE / BASALT
CONGLOMERATE & SANDSTONES
BLACK & GREEN SHALES
SANDSTONE, SILTSTONES & SHALES
FLUVIAL SEDIMENTS
SHALES & SILTSTONES
SHEARED ROCKS
HORNFELS
PALEOZOIC LIMESTONE / DOLOMITE

FIGURE 14.--Schematic distribution of facies in the early Mesozoic basins of eastern North America showing some targets for resource exploration. Modified by Robinson and Gottfried (1985) from C. E. Turner-Peterson.

REFERENCES CITED

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Robinson, G., and Gottfried, D., 1985, U.S. Geological Survey research on mineral resources—1985, in McKelvey Forum program and abstracts: U.S. Geological Survey Circular 925, p. 46-47.

NORTHERN CANADA MINERAL RESOURCE ASSESSMENT

By R. F. J. Scoates, C. W. Jefferson, and D. C. Findlay
Geological Survey of Canada

ABSTRACT

Assessment of Canadian mineral resources began in the 1950's and took the form of national commodity estimates conducted in response to national and international requests. Northern mineral resource assessments have been performed in response to requests from other government agencies and have most frequently been related to native peoples land claim negotiations and to the proposed establishment of northern national parks. The northern mineral and energy resource assessment process is coordinated and administered by two Federal Government interdepartmental committees established in 1980, and the assessments themselves are performed by the Geological Survey of Canada (GSC).

Northern resource assessments consist of two phases. Phase 1 is basically paper research. and phase 2 includes, in addition, on-site geologic examination. The assessment process includes (1) definition of the study area, (2) compilation of geology from existing sources and establishment of geologic domains, (3) inventory and appraisal of mineral and energy resources in the study area, and (4) application of conceptual deposit models to the study area followed by qualitative assessment.

Banks Island, where two park areas are proposed, is an example of a current GSC resource assessment study. The study area includes all of Banks Island and the western part of Victoria Island. One of the geologic domains present comprises late Proterozoic platformal strata, basalts and related sills to which a volcanic red bed copper deposit model has been applied. Disseminated native copper and copper sulfide veins are known to occur in the basalts, although economic deposits have yet to be found. No major differences are apparent between attributes of the deposit model and those of the geologic domain. The rating for the occurrence of undiscovered red bed copper deposit type is therefore high. Similarly, the sandstone-hosted uranium deposit model aaplied to Cretaceous sandstones has been applied to another domain.

The need for periodic reassessment of previously assessed areas can be evaluated by using an historically based resource assessment matrix. The two-dimensional matrix consists of metal commodities plotted along one axis and time plotted along the other. axis. An area in southeastern Manitoba that possesses a well-documented exploration and mining history has been chosen to illustrate the matrix. The historically based resource assessment matrix illustrates the importance of time in terms of changing potential ratings for commodities as well as in terms of increasing confidence levels for commodity ratings, regardless of whether the ratings themselves change with time.

INTRODUCTION

Sangster (1983) comprehensively reviewed the Canadian experience in mineral resource assessment to 1982. He concluded that, within the Geological Survey of Canada (GSC), the most widely used technique in resource assessment surveys is the conceptual model. This technique is versatile, because it can be readily adapted to suit a wide range of data bases, time constraints, commodities, and presentation formats, and it makes extensive use of composite geologic models of deposit types against which the geology of the area being assessed can be compared. Assessment studies currently being published as open-file assessment reports can be used for government land use decisions as well as for mineral exploration.

Selected GSC resource assessment studies in northern Canada are listed in table 1. Early assessment studies took the form of national commodity estimates conducted in response to both national and international requests. An example of the former were the 1972 and 1976 estimates of Canada's undiscovered resources of Cu, Ni, Pb, Zn, Mo, U, and Fe (Energy, Mines and Resources Canada, 1977a, b). The Uranium Resource Appraisal Group process is another such example, established in 1974 to provide an annual audit of Canada's uranium resources. The assessment of uranium resources in Canada (Ruzicka, 1977a, b) has been based on deposit type, as has that of iron ore in Canada (Gross, 1970), as part of a United Nations world survey.

The northern Mineral and Energy Resource Assessment (MERA) process is now coordinated by two committees (fig. 1), which were established in 1980 in response to northern national parks policy legislation by the Government of Canada. The new park policies, formalized in 1972, directed the Department of Indian Affairs and Northern Development (now Indian and Northern Affairs Canada) to compile an inventory of the nonrenewable resource potential of areas in the Yukon and Northwest Territories before their formal establishment as new national parks. The MERA process was established as the mechanism for implementing this directive. The senior MERA committee (fig. 1) comprises the assistant deputy ministers of Indian and Northern Affairs Canada (DINA), Energy Mines and Resources Canada (EMR), and Parks Canada (PC). The working MERA committee comprises senior staff members in the same departments.

These two MERA committees coordinate and administer the northern mineral and energy resource assessments, which use EMR and DINA research systems (fig. 2). A generalized flow chart illustrating responsibilities and ideal timeframes for assessment report production is shown in figure 2. The mineral assessments are done by staff of the Economic Geology Subdivision of GSC. Hydrocarbon assessments are done principally by staff of the GSC's Institute of Sedimentary and Petroleum Geology (ISPG) in Calgary. The preparation of the overall assessment reports is the responsibility of Economic Geology Subdivision.

The reasons for mineral resource assessments have been varied, but most assessments have been in response to outside requests from other government agencies. Areally limited resource assessments in Canada north of lat 60° (fig. 3) have most frequently been related to requirements for native peoples land claim negotiations and to the proposed establishment of northern national parks (fig. 4). Less frequently, the motivations stem from the development of other northern policies, including guidelines for exploration, wilderness assessment, and pipeline and transportation development. Future requests may arise more frequently as a result of native peoples land settlements (Indian and Northern Affairs Canada, 1985) (see later section on Banks and Victoria Islands).

Basic research fueled by curiosity is another motivation for resource assessments. Agterberg and others' (1981) study, for example, compared geomathematical methodology with the analog approach used by the Geological Survey of Canada (1980). Current northern assessments are integrated with systematic geologic mapping and regional metallogenic studies and are of potential interest to exploration companies. Byproducts of resource assessment studies include new geologic maps (Jefferson and others, 1985; Henderson and others, 1986; Jackson and Sangster, in preparation), new stratigraphic and mineral deposit information (Jefferson and others, 1985), and the discovery of new mineral showings such as lead-zinc veins in the Artillery Lake area (Roscoe and others, in preparation).

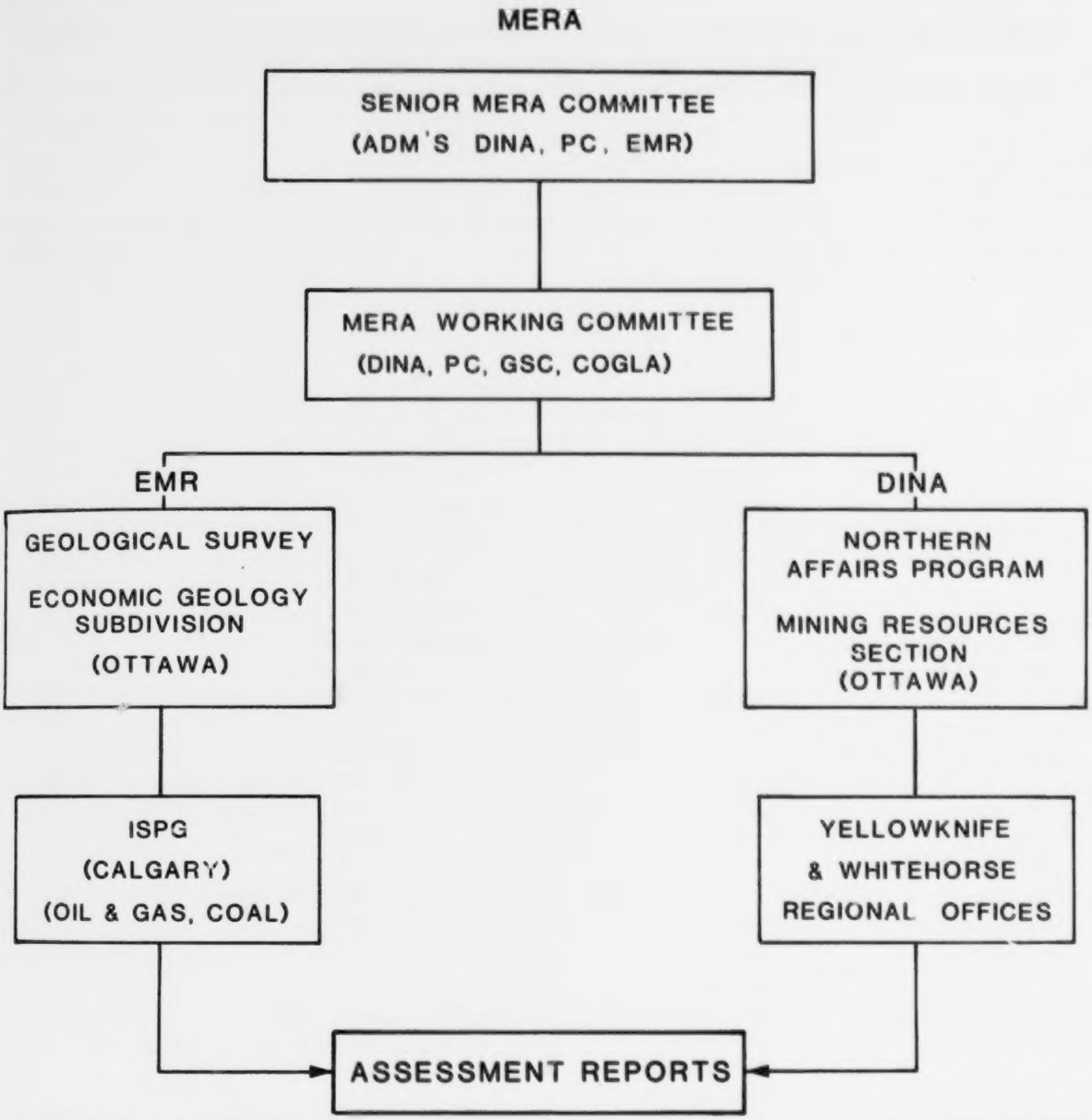

MERA
SENIOR MERA COMMITTEE
(ADM'S DINA, PC, EMR)
MERA WORKING COMMITTEE
(DINA, PC, GSC, COGLA)
EMR
DINA
GEOLOGICAL SURVEY
ECONOMIC GEOLOGY SUBDIVISION
(OTTAWA)
NORTHERN AFFAIRS PROGRAM
MINING RESOURCES SECTION
(OTTAWA)
ISPG
(CALGARY)
(OIL & GAS, COAL)
YELLOWKNIFE & WHITEHORSE REGIONAL OFFICES
ASSESSMENT REPORTS

FIGURE 1.--Coordination of MERA for northern Canada. ADM, assistant deputy minister; DINA, Department of Indian and Northern Affairs Canada; EMR, Energy, Mines and Resources Canada; GSC, Geological Survey of Canada; COGLA, Canadian Oil and Gas Lands Administration; ISPG, Institute of Sedimentary and Petroleum Geology, a Division of GSC based in Calgary.

CURRENT METHODOLOGY

Proposed national parks in northern Canada represent large areas. Assessments of park areas, however, are organized by geologic domains, which are commonly orders of magnitude larger than the proposed parks. This situation has necessitated the

TABLE 1. Selected Geological Survey of Canada mineral resource assessment studies affecting northern Canada (after Sangster, 1983)
(For an example of hydrocarbon resource assessment, see Procter and others (1984))

Study	Area	Commodity reported	Method	Form of results[1]
Lang (1958)	Canada	U	Geologic	QL
Gross (1965)	Canada	Fe	Geologic	QN
Roscoe (1966)	Canada	U, Th	Geologic	QN
Gross (1970)	Canada, West Indies.	Fe	Geologic	QN
Barry and Freyman (1970).	Northern British Columbia, Yukon.	Various	Subjective probability (Delphi)	QN
De Geoffrey and Wu (1970).	Canadian Shield.	Various ($ values).	Probabilistic.	QN
Derry (1973)	Arctic and sub-Arctic.	Cu, Pb, Zn, Au, Fe.	Geologic	QN
Energy, Mines and Resources Canada (1977a).	Canada	Cu, Pb, Zn, Mo, Ni.	Geologic	QN
Energy, Mines and Resources Canada (1977b).	Canada	Fe	Geologic	QN
Ruzicka (1977)	Canada	U	Geologic	QL
Geological Survey of Canada (1978).	Western Arctic	Various	Geologic	QL
Geological Survey of Canada (1980).	Proposed parks, Yukon and Northwest Territories.	Various	Geologic	QL
Economic Geology Division (1980).	Northern Yukon and parts of Northwest Territories.	Various	Geologic	QL
Agterberg and others (1981).	Southern district of Keewatin, Northwest Territories.	Various	Geostatistical.	QL
Findlay and others (1981).	Arctic islands	Various	Geologic	QL
Geological Survey of Canada (1981a).	Northern Yukon	Various	Geologic	QL
Geological Survey of Canada (1981b).	Northern Ellesmere Island.	Various	Geologic	QL
Sinclair and others (1981).	Yukon	Various	Geologic	QL

TABLE 1. Selected Geological Survey of Canada mineral resource assessment studies affecting northern Canada (after Sangster 1983)—Continued

Study	Area	Commodity reported	Method	Form of results[1]
Labovitz and Griffiths (1982).	Canada	Various ($ values).	Geostatistical.	QN
Roscoe (1984)	Bathurst Inlet, Northwest Territories.	Various	Geologic	QL
Jackson and Sangster (in press).	Northern Baffin Island, Northwest Territories.	Various	Geologic (new maps).	QL
Roscoe and others (in press).	East Arm, Great Slave Lake, Northwest Territories.	Various	Geologic, geochemical.	QL
Jefferson and Scoates (in preparation).	Banks-Victoria Islands, Northwest Territories.	Various	Geologic, geochemical.	QL
C. W. Jefferson and R. F. J. Scoates (work in progress).	Wager-Southampton, Northwest Territories.	Various	Geologic, geochemical (phase 2).	QL
C. W. Jefferson (work in progress).	Nahanni, Northwest Territories.	Various	Geologic, geochemical (phase 2).	QL

[1] QL, qualitative; QN, quantitative.

establishment of study areas (fig. 5) that not only encompass the proposed park boundaries but also include larger, more geologically representative areas. These larger assessment domains (1) provide more confidence in the subjective assessments of resource potential, (2) can be chosen to fit the National Topographic System grid in a rational way, and (3) allow subsequent adjustments to proposed park boundaries with the compiled data base.

Methods of resource assessment have been summarized by the Economic Geology Division (1980) and Sangster (1983). Mineral deposit models such as those in expert compilations edited by Eckstrand (1984) and Cox (1983) provide analogs. The applicability of a given analog to a given domain is subjective and qualitative, based on the proportion and relative weighting of those attributes considered essential to that ore deposit type that are present in the terrane (see Discussion Group 3, this volume). The extent of the geologic and metallogenic knowledge of an area determines the confidence in the analog application (see later section on the need for continuing reassessment). Typical qualitative ratings are shown in table 2. Some assessments (Economic Geology

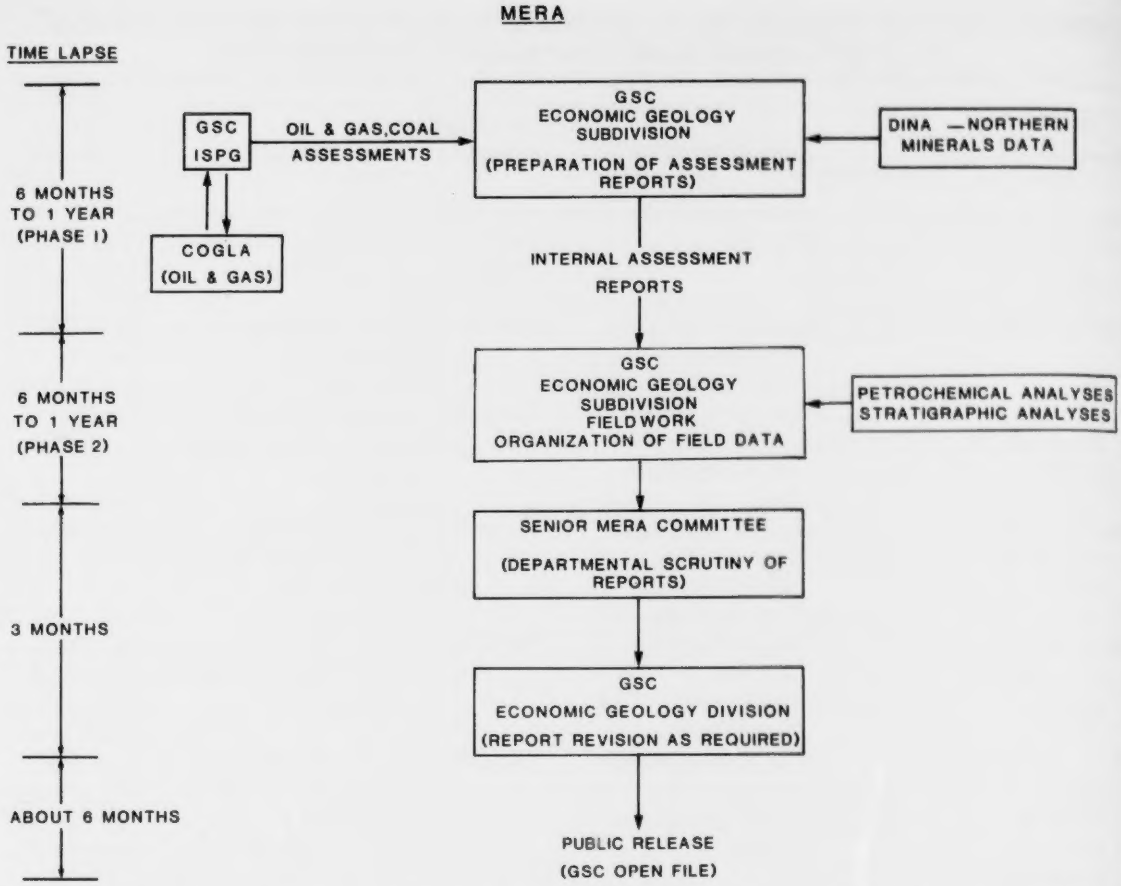

MERA
TIME LAPSE
6 MONTHS TO 1 YEAR (PHASE 1)
6 MONTHS TO 1 YEAR (PHASE 2)
3 MONTHS
ABOUT 6 MONTHS
GSC ISPG
OIL & GAS,COAL ASSESSMENTS
COGLA (OIL & GAS)
GSC ECONOMIC GEOLOGY SUBDIVISION (PREPARATION OF ASSESSMENT REPORTS)
DINA —NORTHERN MINERALS DATA
INTERNAL ASSESSMENT REPORTS
GSC ECONOMIC GEOLOGY SUBDIVISION FIELDWORK ORGANIZATION OF FIELD DATA
PETROCHEMICAL ANALYSES STRATIGRAPHIC ANALYSES
SENIOR MERA COMMITTEE (DEPARTMENTAL SCRUTINY OF REPORTS)
GSC ECONOMIC GEOLOGY DIVISION (REPORT REVISION AS REQUIRED)
PUBLIC RELEASE (GSC OPEN FILE)

FIGURE 2.—Phases of the northern MERA process. ADM, assistant deputy minister; DINA, Department of Indian and Northern Affairs Canada; EMR, Energy, Mines and Resources Canada; GSC, Geological Survey of Canada; COGLA, Canadian Oil and Gas Lands Administration; ISPG, Institute of Sedimentary and Petroleum Geology, a Division of GSC based in Calgary.

Division, 1980) have also rated the potential for the economic development of inferred resources, considering exploitability factors such as transport and other logistics.

Two phases of resource assessments are made (time lapse, fig. 2). Phase 1, mainly paper research, includes (1) definition of the study area; (2) establishment of geologic domains; (3) compilation of geology from existing sources and inventory and appraisal of mineral and energy resources within the study area using the available information base, with emphasis on metallic commodities and hydrocarbons; and (4) application of conceptual deposit models to the study area, followed by qualitative assessment using the rating categories in table 2.

Phase 2 can be more varied than phase 1, incorporating one or more additional aspects. New information can be collected by means of new bedrock mapping, new surficial mapping, geobotanical studies, remote sensing studies, paleontological studies, stratigraphic studies, and exploration geochemical studies. Phase 1 can be combined with phase 2 if time is short (for example, Nahanni) or if the existing data base is extremely limited (for example, Wager-Southampton).

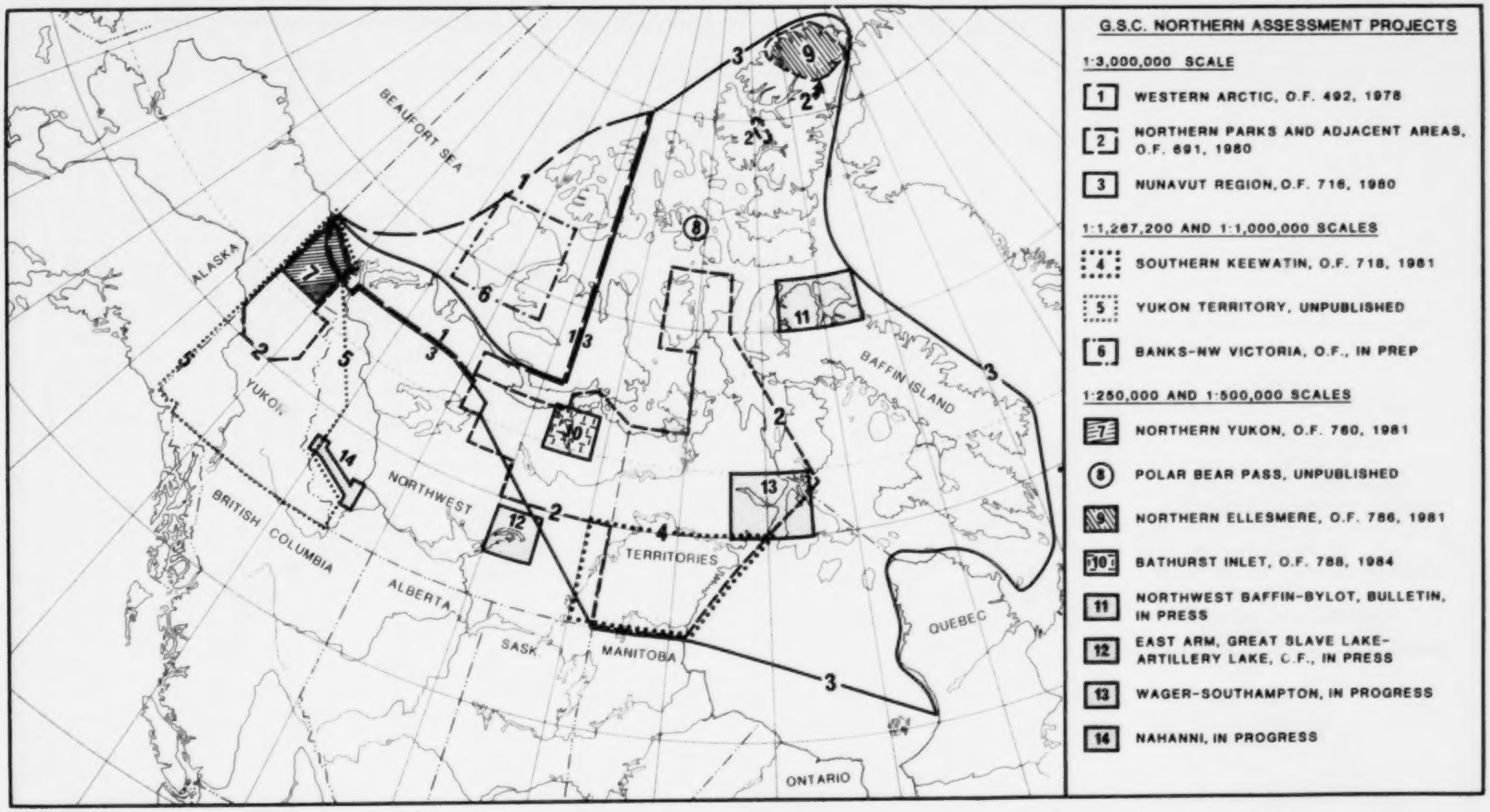

G.S.C. NORTHERN ASSESSMENT PROJECTS
1:3,000,000 SCALE
1 WESTERN ARCTIC, O.F. 492, 1978
2 NORTHERN PARKS AND ADJACENT AREAS, O.F. 691, 1980
3 NUNAVUT REGION, O.F. 716, 1980
1:1,267,200 AND 1:1,000,000 SCALES
4 SOUTHERN KEEWATIN, O.F. 718, 1981
5 YUKON TERRITORY, UNPUBLISHED
6 BANKS-NW VICTORIA, O.F., IN PREP
1:250,000 AND 1:500,000 SCALES
7 NORTHERN YUKON, O.F. 760, 1981
8 POLAR BEAR PASS, UNPUBLISHED
9 NORTHERN ELLESMERE, O.F. 786, 1981
10 BATHURST INLET, O.F. 788, 1984
11 NORTHWEST BAFFIN-BYLOT, BULLETIN, IN PRESS
12 EAST ARM, GREAT SLAVE LAKE-ARTILLERY LAKE, C.F., IN PRESS
13 WAGER-SOUTHAMPTON, IN PROGRESS
14 NAHANNI, IN PROGRESS
BEAUFORT SEA
ALASKA
YUKON
BRITISH COLUMBIA
NORTHWEST
TERRITORIES
ALBERTA
SASK.
MANITOBA
ONTARIO
QUEBEC
BAFFIN ISLAND

FIGURE 3.—GSC regional resource assessment projects in northern Canada. After Sangster (1983).

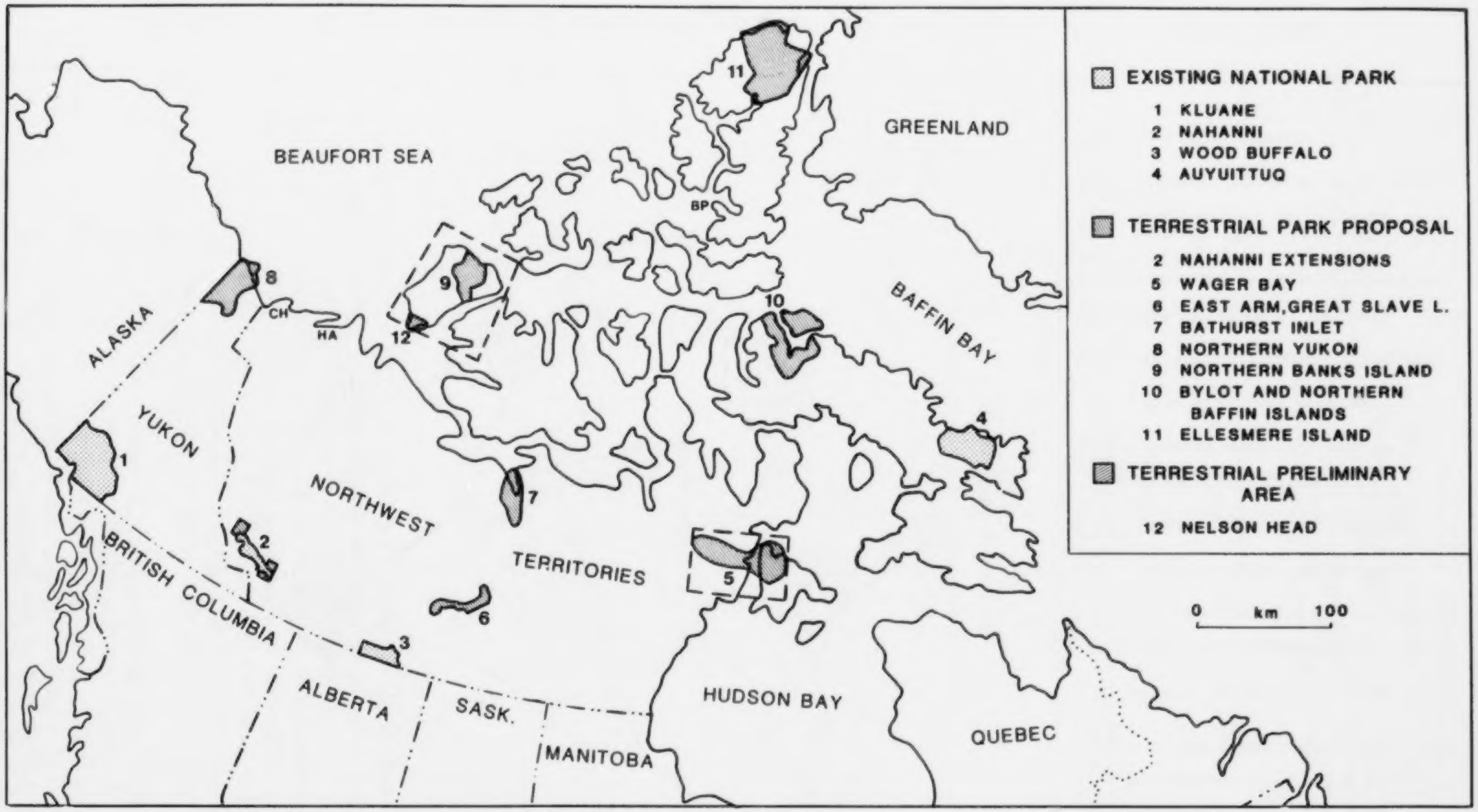

BEAUFORT SEA
GREENLAND
BAFFIN BAY
HUDSON BAY
QUEBEC
ALASKA
YUKON
NORTHWEST
TERRITORIES
BRITISH COLUMBIA
ALBERTA
SASK.
MANITOBA
CH
HA
BP
1
2
3
4
5
6
7
8
9
10
11
12
EXISTING NATIONAL PARK
1 KLUANE
2 NAHANNI
3 WOOD BUFFALO
4 AUYUITTUQ
TERRESTRIAL PARK PROPOSAL
2 NAHANNI EXTENSIONS
5 WAGER BAY
6 EAST ARM,GREAT SLAVE L.
7 BATHURST INLET
8 NORTHERN YUKON
9 NORTHERN BANKS ISLAND
10 BYLOT AND NORTHERN BAFFIN ISLANDS
11 ELLESMERE ISLAND
TERRESTRIAL PRELIMINARY AREA
12 NELSON HEAD
0 km 100

FIGURE 4.—Index map of parks and proposed parks in northern Canada (Parks Canada, 1978a, b, c, d, e, f, 1983a, b, 1984a, b, 1985a, b). CH (Caribou Hills) includes Pingos of Tuktoyaktuk proposed park. BP (Bjorne Peninsula) and HA (Horton-Anderson Plain) are small preliminary park areas.

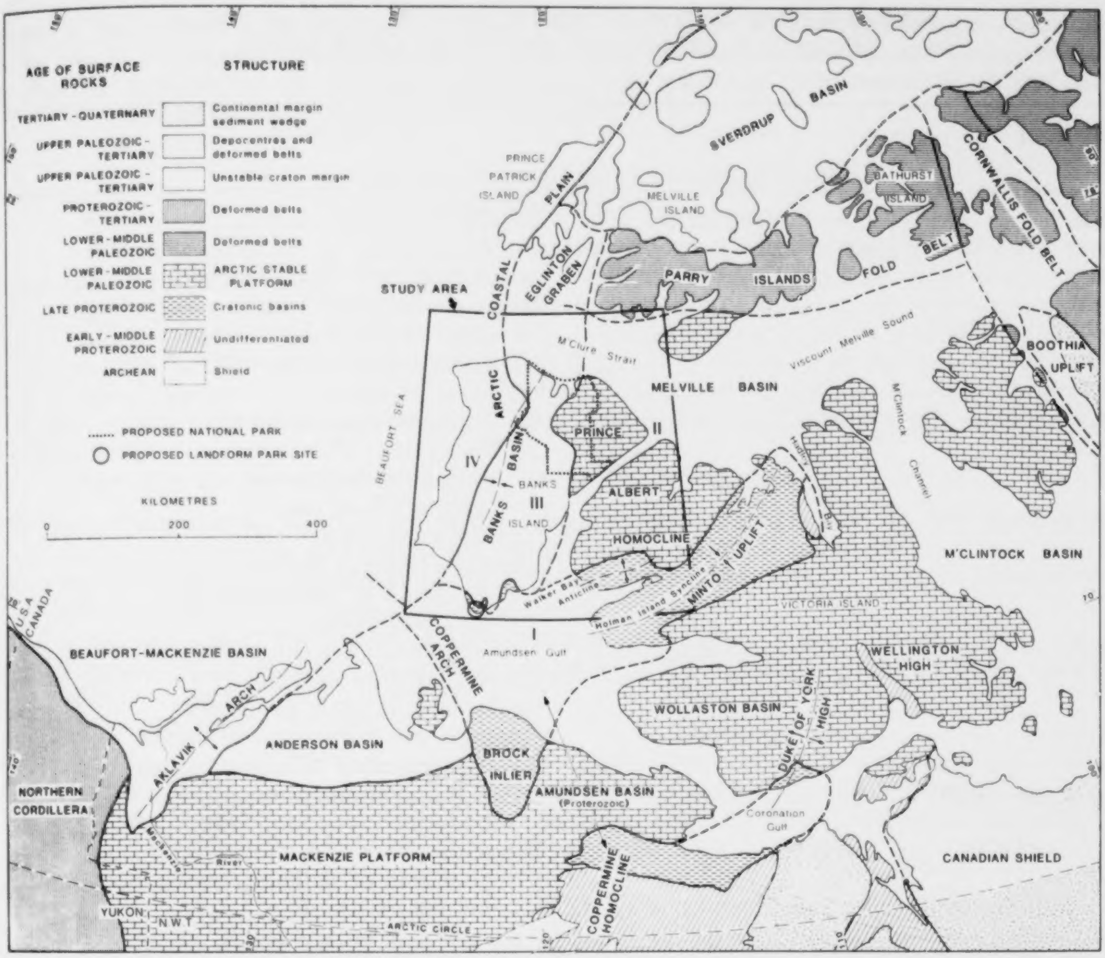

AGE OF SURFACE ROCKS
STRUCTURE
TERTIARY - QUATERNARY
Continental margin sediment wedge
UPPER PALEOZOIC - TERTIARY
Depocentres and deformed belts
UPPER PALEOZOIC - TERTIARY
Unstable craton margin
PROTEROZOIC - TERTIARY
Deformed belts
LOWER - MIDDLE PALEOZOIC
Deformed belts
LOWER - MIDDLE PALEOZOIC
ARCTIC STABLE PLATFORM
LATE PROTEROZOIC
Cratonic basins
EARLY - MIDDLE PROTEROZOIC
Undifferentiated
ARCHEAN
Shield
PROPOSED NATIONAL PARK
PROPOSED LANDFORM PARK SITE
KILOMETRES
0
200
400
SVERDRUP BASIN
PRINCE PATRICK ISLAND
COASTAL PLAIN
EGLINTON GRABEN
MELVILLE ISLAND
BATHURST ISLAND
CORNWALLIS FOLD BELT
PARRY ISLANDS FOLD BELT
STUDY AREA
M'Clure Strait
Viscount Melville Sound
MELVILLE BASIN
BOOTHIA UPLIFT
M'Clintock Channel
BEAUFORT SEA
ARCTIC
BANKS BASIN
IV
BANKS ISLAND
III
PRINCE
II
ALBERT
HOMOCLINE
MINTO UPLIFT
Walker Bay Anticline
Holman Island Syncline
VICTORIA ISLAND
M'CLINTOCK BASIN
I
Amundsen Gulf
USA
CANADA
BEAUFORT-MACKENZIE BASIN
COPPERMINE ARCH
WELLINGTON HIGH
WOLLASTON BASIN
DUKE OF YORK HIGH
AKLAVIK ARCH
ANDERSON BASIN
BROCK INLIER
AMUNDSEN BASIN (Proterozoic)
Coronation Gulf
NORTHERN CORDILLERA
MACKENZIE PLATFORM
Mackenzie River
COPPERMINE HOMOCLINE
CANADIAN SHIELD
YUKON
N.W.T.
ARCTIC CIRCLE

FIGURE 5.--Metallogenic domains of the western Arctic (after Miall, 1976). The Banks and northwestern Victoria Islands study area and the enclosed proposed parks are shown by solid lines. Assessment domains I, II, III, and IV are explained in text.

CURRENT GSC RESOURCE ASSESSMENT ACTIVITIES IN NORTHERN CANADA

Many resource assessment studies dealing with northern Canada (table 1) have been in response to Parks Canada activities. Four established, 10 proposed, and 3 preliminary national park and park reserve areas are located in northern Canada (fig. 4). Seven of the areas were proposed in 1978 (Parks Canada, 1978a, b, c, d, e, f) and assessed together, on a regional basis (Geological Survey of Canada, 1980). More detailed assessments for individual proposed parks were undertaken beginning in 1981. Three current assessment studies (Banks Island-northwestern Victoria Island, Wager Bay-Southampton Island, and Nahanni) are summarized in this paper.

The Wager Bay and Nahanni areas are the first whose phase 2 (field) assessments are being supported by joint funding from Environment Canada (of which Parks Canada is a branch), Indian and Northern Affairs Canada, and Energy Mines and Resources Canada (of which the GSC is a branch). Most previous resource assessments did not include a

TABLE 2.—Explanation of mineral potential rating categories (Slightly modified after Sinclair and Leech (1982))

Symbol	Potential	Criteria
VH----------------	Very high	Geologic environment very favorable. Significant deposits known. Based on deposit models; presence of additional (undiscovered) deposits very likely.
H-----------------	High	Geologic environment very favorable, although significant mineral deposits may not be known to be present. Based on deposit models; presence of undiscovered deposits likely.
MH----------------	Moderate to high.	Intermediate between moderate and high potential. Reflects greater uncertainty
M-----------------	Moderate	Geologic environment favorable, regardless of whether mineral occurrences are known. Based on deposit models; presence of undiscovered mineral deposits possible.
LM----------------	Low to moderate.	Intermediate between low and moderate potential. Reflects greater uncertainty.
L-----------------	Low	Some aspects of the geologic environment may be favorable but are limited in extent. Few, if any, mineral occurrences known. Probability that undiscovered mineral deposits are present is low.
VL----------------	Very low	Geologic environment unfavorable No known mineral deposits or occurrences present. Possibility unlikely that undiscovered mineral deposits of the type being assessed for are present.

phase 2 field component because of time constraints and the fact that the cost would have had to be supported entirely by the GSC. In 1986, we will also obtain considerable helicopter support for our northern operations from the Polar Continental Shelf Project of the Department of Energy, Mines and Resources.

Banks and Northwestern Victoria Islands Resource Assessment Project

Two park areas are proposed for Banks Island—one at the northeastern end and the other at the southern tip (Parks Canada, 1978a). These proposed park areas, the enclosing resource assessment study area, and geologic domains in the region are illustrated in figure 5. The study area includes the northwestern part of Victoria Island to gain a better perspective of the regional metallogenic framework of the area containing the proposed parks. A brief summary and two examples of ratings based on mineral deposit models are taken from the resource assessment by Jefferson and Scoates (in preparation).

Resource assessment was based on four geologic domains:

I. Late Proterozoic platformal strata, basalts, and related sills of the Amundsen Embayment (Young and Jefferson, 1975; Young, 1981).
II. Cambrian to Late Devonian platformal strata of the Prince Albert Homocline (Thorsteinsson and Tozer, 1962; Miall, 1976).
III. Clastic deposits of the Banks Basin, an unstable cratonic margin (Miall, 1979).
IV. Unconsolidated fluvial and glacial deposits of the Arctic Coastal Plain (Miall, 1979).

The above domains are defined after Miall (1976, 1979), whose bedrock studies followed reconnaissance mapping by Thorsteinsson and Tozer (1962). Surficial mapping by Vincent (1982, 1983) and a variety of local studies such as those by Gibbins and others (1986) and Jefferson and Scoates (in preparation) also influenced the definition of geologic domains.

Phase 2 resource assessment for this study area has involved (1) compilation of existing geologic literature on the area, (2) reanalysis of regional till samples collected by Vincent (1982, 1983) for his studies of glacial processes, (3) a 2-week field program to confirm and sample mineral occurrences and (or) geologically favorable sites within the study area, and (4) application of mineral deposit models to the domains. Little additional information has been published since the original phase 1 resource assessments were done by the Economic Geology Division (1980).

Deposit Model Application I: Volcanic Red Bed Copper

Native copper was known to exist in the Natkusiak Basalts (domain I) before European explorers arrived (Stefansson, 1913). Widespread exploration in the 1960's and again in the 1980's (Nelson, 1983) has confirmed the existence of disseminated to large plates of native copper and copper sulfide veins, but economic deposits have yet to be found. The stratigraphic settings and varieties of the occurrences have been given by Jefferson and others (1985). The following features of occurrences in the Natkusiak Basalts correspond closely with those listed by Kirkham (1984) for the volcanic red bed copper deposit type:

Commodities: Cu (Ag)
Typical grade: <0.1 to >4.0 percent Cu
Geologic setting: Continental to shallow marine, low-latitude environment in continental-rift-related flood basalt sequence.

Host rocks: Amygdaloidal flows; mafic tuff and breccia; at boundaries of interlayered red sedimentary rocks; anoxic pyritic tuffs interlayered with flows and red bed sequence. Underlain (unconformably) by carbonates and bedded evaporites.

Form of occurrences: Highly variable, typically peneconcordant in permeable units such as amygdaloidal flow tops.

Metallic minerals: Native copper, chalcocite, bornite, bornite,chalcopyrite, pyrite, and native silver.

Associated minerals: Calcite, quartz, epidote, prehnite, and pumpellyite.

Textures: Replacement and void filling; intergrown with low-grade metamorphic minerals prehnite and pumpellyite.

No major differences are apparent between the attributes of the deposit model and those of domain I. The rating for the occurrence of undiscovered volcanic red bed copper deposit type in domain I is therefore high (H). The only uncertainty is how large and high grade these occurrences might be on Victoria Island. Similar deposits elsewhere have been larger than 50 million tons and contained more than 4.0 percent Cu (Kirkham, 1984; Weege and Pollack, 1971) (not necessarily in the same deposit).

Deposit Model Application II: Sandstone-Hosted Uranium

Sandstone-hosted uranium potential has not been considered for domain III in previous resource assessments. According to deposit type descriptions by Gandhi (1980), Hodges (1983), and Ruzicka and Bell (1984), the following aspects of the Early Cretaceous Isachsen and Christopher Formations and sand members of the Late Cretaceous Kanguk Formation in domain III are favorable for sandstone uranium deposits:

Host rocks: Sandstones are fluviatile, semiconsolidated, and feldspathic; organic matter (a reducing agent) is locally abundant; and tuffs (possible source of uranium) are present.

Age: Mesozoic to Tertiary, like deposits in the Southwestern United States.

Geologic setting: Depositional environment was an unstable coastal plain; faulting was active during sedimentation.

Genetic processes: Lower Isachsen Formation sands are pink to white, underlain by weathered sandstones of the Proterozoic Glenelg Formation. This coloration indicates that source areas were oxidized, in contrast to the general drab color of overlying sands of the upper Isachsen, Christopher, and Kanguk Formations. Oxidation reduction reactions were therefore possible.

The only negative factor is that anomalous radioactivity has not yet been detected in this remote area, possibly a function of the lack of exploration for this kind of deposit on Banks Island. The moderate to high (MH) rating assigned to this domain for sandstone-hosted uranium reflects the large number of geologically favorable features present and the uncertainty caused by the lack of radioactive occurrences.

Wager Bay-Southampton Island Resource Assessment Project

Resource assessment of this area (fig. 6) commenced in response to a general proposal of interest by Parks Canada (1978b) in the Wager Bay area; its 1984 field assessment indicated that the Ford Lake area has the greatest park potential, although White Island and Duke of York Bay also are being considered (M. McComb, personal communication, 1984). On the basis of these indications, the resource assessment area was defined to include a larger area encompassing Wager Bay and northwestern Southampton Island (fig. 6).

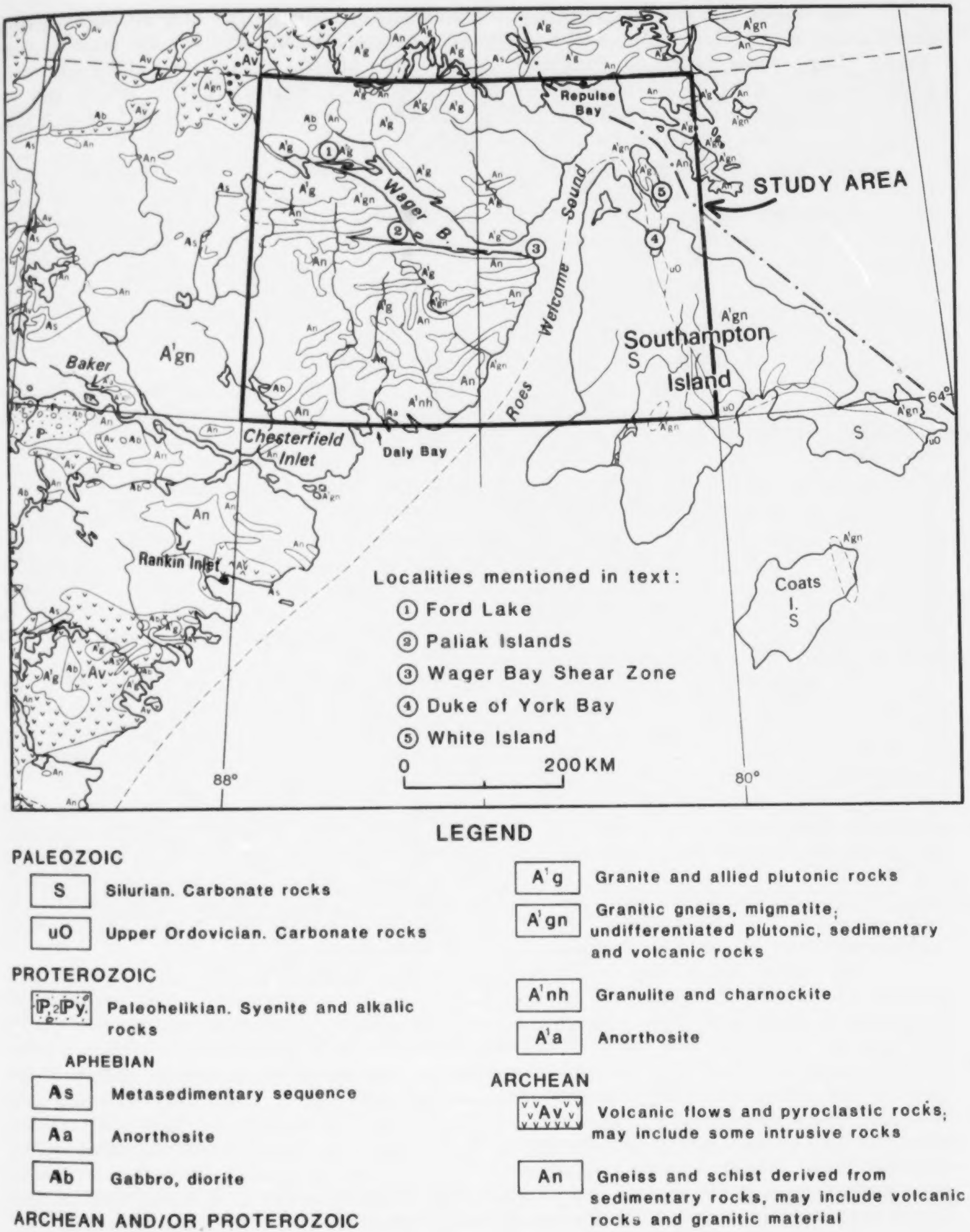

STUDY AREA
Repulse Bay
Wager B.
Roes Welcome Sound
Southampton Island
Baker L.
Chesterfield Inlet
Daly Bay
Rankin Inlet
Coats I.
64°
88°
80°
Localities mentioned in text:
① Ford Lake
② Paliak Islands
③ Wager Bay Shear Zone
④ Duke of York Bay
⑤ White Island
0 200 KM
LEGEND
PALEOZOIC
S Silurian. Carbonate rocks
uO Upper Ordovician. Carbonate rocks
PROTEROZOIC
P2Py Paleohelikian. Syenite and alkalic rocks
APHEBIAN
As Metasedimentary sequence
Aa Anorthosite
Ab Gabbro, diorite
ARCHEAN AND/OR PROTEROZOIC
A'g Granite and allied plutonic rocks
A'gn Granitic gneiss, migmatite, undifferentiated plutonic, sedimentary and volcanic rocks
A'nh Granulite and charnockite
A'a Anorthosite
ARCHEAN
Av Volcanic flows and pyroclastic rocks; may include some intrusive rocks
An Gneiss and schist derived from sedimentary rocks, may include volcanic rocks and granitic material

FIGURE 6.— Geology of the Wager Bay-Southampton region (from Douglas, 1968).

The Wager Bay area is very remote and poorly known. The nearest communities are Rankin Inlet, Baker Lake, and Repulse Bay, some 500, 500, and 300 km from central Wager Bay, respectively. Published maps are based mainly on 1:500,000-scale reconnaissance work by Heywood (1967) and Heywood and Sanford (1976). Wager Bay has not been sounded, nor is its bottom geology known. The status of the geology in this area before our current assessment is shown in figure 6.

Resource assessment commenced in 1985 with 1:50,000-scale geologic mapping around the shores of Wager Bay. Fieldwork combined projects from the Economic Geology and Mineralogy Division and the Precambrian Geology Division (Henderson and others, 1986). Mapping was concentrated in three areas of interest indicated on figure 6: (1) a belt of Hudsonian granites (A^1g) that trends through Ford Lake and cuts across the northwestern corner of the study area; (2) a belt of supracrustal gneisss (An and A^1gn) near Paliak Islands; and (3) a prominent east-west shear zone delimiting the southeastern margin of Wager Bay. The first two areas were selected for their mineral potential, and the third area was selected for its regional tectonic significance.

Preliminary geologic results reported by Henderson and others (1986) are summarized here in relative chronological order. In area 2, banded orthogneiss and amphibolite-grade supracrustal rocks of Archean or Early Proterozoic age were multiply deformed and attenuated and subsequently intruded by quartz diorite to granite sills. All of these units were deformed into large open to tight folds. Gneissic rocks in areas 1 and 2 are similar and were intruded by Early Proterozoic plutons. In area 1, these rocks form a belt of type I composite batholiths, some of which are fluorite bearing, exhibiting distinctive aeromagnetic anomaly patterns (Geological Survey of Canada, 1984a, b). Some are fluorite bearing. Similar flourite-bearing granitoid rocks, particularly concentrated in the Nueltin Lake-Ennadai Lake district, intrude a variety of older rocks in extensive areas in the southern Keewatin district (Eade, 1973; LeCheminant and others, 1976, 1977, 1980; Reinhardt and Chandler, 1973).

The gneisses and type I plutons are mylonitized in a zone at least 25 km wide that bounds the southeastern part of Wager Bay. This shear zone includes a component of pervasive dextral shear, which is evident both in outcrop and on the aeromagnetic map (Geological Survey of Canada, 1984a). It also includes discrete sinistral components, but the overall sense of movement is dextral. The net slip is unknown.

Geologic domains for resource assessment on the same scale as those of the Banks-Victoria Islands area will be finalized after next season's geologic mapping. Potential domains include extensions of the three study areas described above, the broad Precambrian and Paleozoic map units of White Island (area 5) and Southampton Island, and the Daly Bay metamorphic complex (Aa and A^1nh, fig. 6) Gordon, 1971, 1972). The vast areas of undifferentiated granitic gneiss and migmatite (A^1gn) may remain undifferentiated, at least for purposes of resource assessment.

Key rock units for resource assessment attention are the Precambrian supracrustal units, the granitoid intrusions, and the Paleozoic rocks. The Precambrian supracrustal units are thin, severely attenuated and dismembered, and predominantly sedimentary in origin; few mafic rocks are present. The granitoid rocks occupy a broad belt trending northeasterly through the heart of the proposed parkland. Some of the plutons are fluorite bearing and resemble intrusions of the Nuelton Lake-Ennadai Lake district, some of which are associated with minor gold anomalies (Charbonneau and Swettenham, 1986). The Paleozoic rocks on Southampton Island include Ordovician and Silurian reefs, which deserve special attention because of their hydrocarbon and lead-zinc potential, and oil shales, which are being studied at ISPG. These features were previously suggested as exploration targets by Sangster (1970) and Sanford (1970). A second and final field survey in 1986 will devote more attention to the Paleozoic units and surficial geology while study of the Precambrian units continues.

Nahanni National Park Extensions Resource Assessment Project

Nahanni National Park was established as a reserve in 1974. No resource assessment was made at that time, but it was agreed that adjustments could be made during settlement of native land claims (Parks Canada, 1983a). A popular park, it is a high priority for Parks Canada, and expansions have been proposed recently (Parks Canada, 1984a). These proposals have brought in the MERA process, which will retroactively cover the present park as well as proposed expansions.

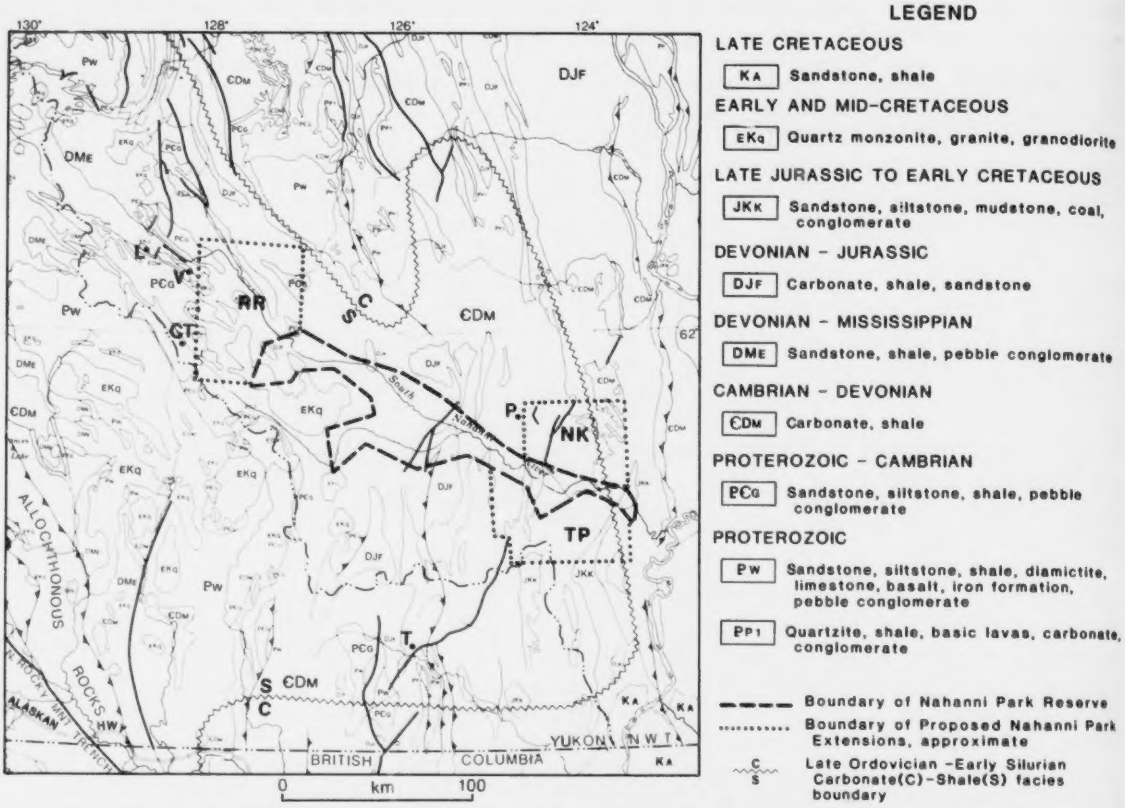
Geologically, the study area includes Late Proterozoic to Late Cretaceous platformal to shale basin sedimentary strata that were deformed during the Tertiary Laramide orogeny and intruded by Devonian to Tertiary granitoid rocks. This geology is summarized in figure 7, which is based on a 1:2,000,000-scale compilation by Tipper and others (1981). Their compilation, in turn, is based on 1:250,000-scale mapping by Blusson (1972), Douglas (1974), Douglas and Norris (1959, 1974a, b, c, 1976a, b, c), Gabrielse and Blusson (1969), Gabrielse and others (1973), Green and others (1968), and Roots and others (1966). Only a few small areas have been studied in greater detail (for example, the Tungsten area (CT) at 1:50,000 scale by Blusson (1968) and the Nahanni (N.T.S. 105I) sheet mapped at 1:50,000 scale by Gordey (1981)) and geochemically sampled by Goodfellow (1982)).

Metallogenically, the reserved and proposed park areas cover a major reentrant of the Selwyn Basin (Gordey and others, 1981), a major carbonate-shale facies change (C-S, fig. 7), and a belt of Mesozoic granitoid intrusions (Sinclair, in press), all of which have important mineral deposits associated with them. Such deposits include the skarn-type Tungsten mine (Mathieson and Clark, 1984), numerous large to small deposits of tungsten, and base metals of skarn, vein, replacement, sedimentary exhalative (Carne and Cathro, 1982), and sedimentary diagenetic (for example, sedimentary copper) type, all indicated on Dawson and others' (1985a) metallogenic map. Hydrocarbon resources include some important coal deposits as well as potential oil and gas reserves (Stott, 1982).

Phase 1 and phase 2 assessments began simultaneously in 1985 with a 10-day orientation in logistics, geology, and geochemical exploration methods. Data acquired by exploration companies in the area have been made available to us on a voluntary basis and are being treated as confidential. Field programs during the next 2 years will include detailed mapping and assessment of mineral showings, lithogeochemical sampling, till sampling, hydrogeologic studies of the numerous cold and hot springs in the area, and updating of parts of the existing 1:250,000-scale geologic maps. These studies will be done in collaboration with personnel from other parts of the GSC, from Indian and Northern Affairs Canada, and from one or more universities. Additional logistic support will be provided by the Polar Continental Shelf Project.

NEED FOR CONTINUING REASSESSMENT

Mineral resource assessment studies involve what is known concerning the geologic framework of the area being assessed (synthesis of available geologic data) and knowledge of deposit models. The more that is known about the geology of the area being assessed, the greater the confidence in the resulting synthesis. The geologic synthesis, in turn, places constraints on the variety of deposit types that might be expected to occur in the area under study. Because large parts of northern Canada have received only reconnaissance-level geologic investigation, only low-confidence geologic syntheses are available for several areas requiring resource assessment statements. Statements of resource potential are, in turn, qualified by considerable uncertainty.



130°
128°
126°
124°
62°
DJF
CDM
DME
Pw
PCG
EKq
RR
NK
TP
P.
T.
CT
L
V
S C
South Nahanni River
JKK
KA
ALLOCHTHONOUS ROCKS
ROCKY MTN TRENCH
ALASKAN HWY
YUKON
N.W.T.
BRITISH COLUMBIA
0 km 100
LEGEND
LATE CRETACEOUS
KA Sandstone, shale
EARLY AND MID-CRETACEOUS
EKq Quartz monzonite, granite, granodiorite
LATE JURASSIC TO EARLY CRETACEOUS
JKK Sandstone, siltstone, mudstone, coal, conglomerate
DEVONIAN - JURASSIC
DJF Carbonate, shale, sandstone
DEVONIAN - MISSISSIPPIAN
DME Sandstone, shale, pebble conglomerate
CAMBRIAN - DEVONIAN
CDM Carbonate, shale
PROTEROZOIC - CAMBRIAN
PCG Sandstone, siltstone, shale, pebble conglomerate
PROTEROZOIC
PW Sandstone, siltstone, shale, diamictite, limestone, basalt, iron formation, pebble conglomerate
PP1 Quartzite, shale, basic lavas, carbonate, conglomerate
Boundary of Nahanni Park Reserve
Boundary of Proposed Nahanni Park Extensions, approximate
C S Late Ordovician - Early Silurian Carbonate(C)-Shale(S) facies boundary

FIGURE 7.—Geology and proposed parks (approximate) of the South Nahanni River area. Proposed park extensions are RR, Ragged Ranges; NK, Nahanni Karst; and TP, Tlogotsho Plateau. Mineral localities mentioned in the text are CT, mining town of Tungsten; L, Lened property; P, Prairie Creek property; T, "Ting Creek" alkalic intrusion; V, Vulcan property. Geology after Tipper and others (1981); mineral localities after Dawson and others (1984).

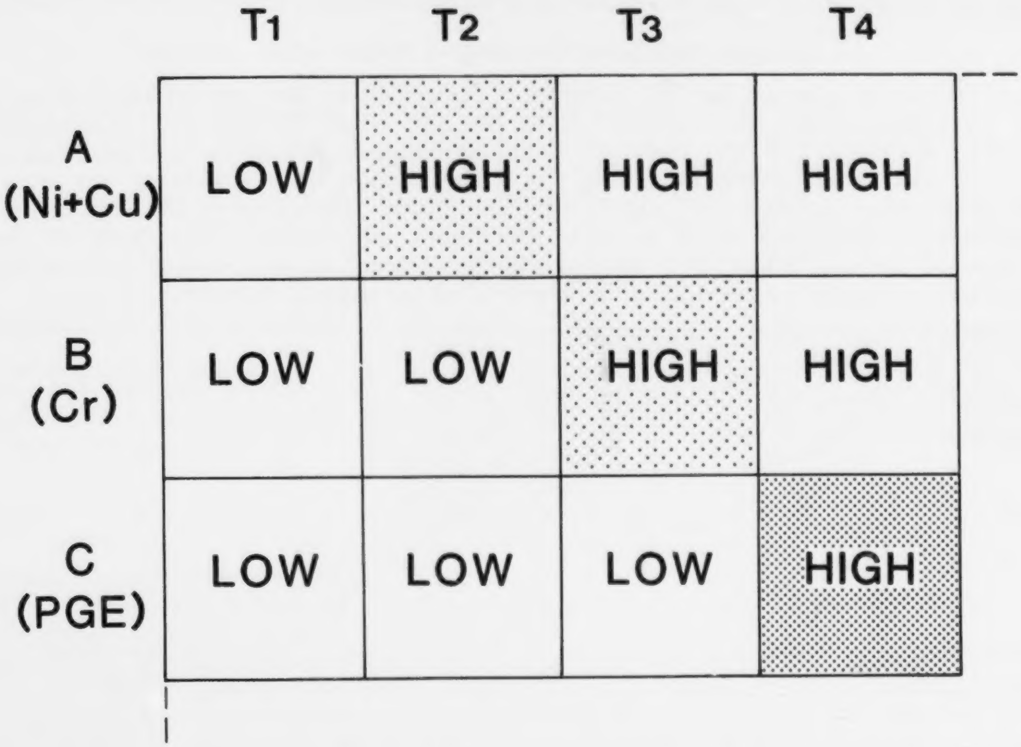
Future geologic mapping programs in northern Canada will raise the level of the geologic data base, and the confidence levels of the syntheses will, in turn, be raised. Future resource assessment studies in northern Canada thus should produce more confident statements of resource potential. Brobst and Goudarzi (1984, p. 7) concisely articulated the need for continuing reassessment:

> Assessments of mineral-resource potential are of a dynamic nature regardless of how they are conducted....Final, once-and-for-all assessments of mineral-resource potential cannot be made. Areas should be reassessed periodically as new data become available, or new concepts of the factors that influence the concentration of minerals are developed, as new uses and extractive technologies for minerals are devised, and as the world's economy changes.

Such thoughts have formed the basic premise of many mineral resource assessment studies, particularly those made in frontier areas where the geoscience data base is of a reconnaissance nature.

AN HISTORICALLY BASED RESOURCE ASSESSMENT MATRIX

One way of illustrating the need for reassessment is to use an historically based resource assessment matrix (fig. 8). This idea was initially inspired by Page and others' (1985) excellent historical review of the exploration and mining of the Stillwater



	T1	T2	T3	T4
A (Ni+Cu)	LOW	HIGH	HIGH	HIGH
B (Cr)	LOW	LOW	HIGH	HIGH
C (PGE)	LOW	LOW	LOW	HIGH

HIGH	The high rating for these commodities is based on their discovery by field exploration techniques
HIGH	The high rating for PGE potential is based in part on the application of a deposit model to the known existence of a layered intrusion

FIGURE 8.—An historically based resource assessment matrix for the Bird River Sill. Time is recorded along the horizontal axis; resource commodities are shown along the vertical axis. The nature of the geologic data base is given in figure 9 and tables 3, 4, and 5. PGE indicates platinum-group elements. T_1, reconnaissance-level geologic maps (1:500,000 and 1:250,000 scales); T_2, same as T_1 but with active exploration; T_3, same as T_2 but with more detailed systematic regional geologic mapping (1:50,000 scale) and other systematic studies (geophysics, geochemistry, surficial geology, and so on); T_4, same as T_3 but includes site-specific thematic geoscience studies (for example, the Muskox Intrusion mapping and drilling program).

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Complex of Montana. In an area that has a well-recorded exploration history, a series of historical benchmarks that record the discovery of economically significant mineralization can be established. Additionally, the nature of the geologic data base can be established for each benchmark. A two-dimensional matrix plotting metal commodities along one axis and time along the other can be constructed. The Bird River area of southeastern Manitoba provides a Canadian example for this matrix, because it possesses known mineral resources and has a well-established exploration history.

An Example: Bird River Sill Area of Southeastern Manitoba

The area selected for this example is restricted to that part of the Archean Bird River greenstone belt that is underlain by the Bird River Sill (fig. 9). As a result, the resource assessment matrix contains nickel and copper, chromite, and platinum-group elements (PGE) as commodities (fig. 8). The dashed lines extending the time and commodity axes indicate that significant benchmarks may occur in the future and that additional commodities could become significant with time. The dates of various systematic surveys, significant benchmarks in exploration and mining, and significant thematic studies for the Bird River area are noted in tables 3, 4, and 5.

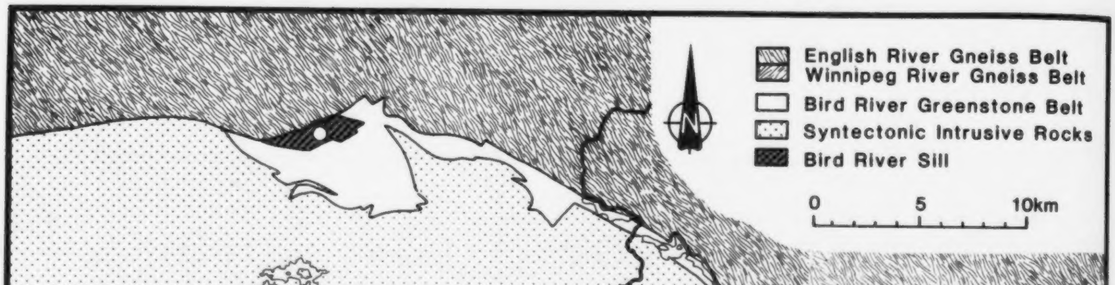
N
English River Gneiss Belt
Winnipeg River Gneiss Belt
Bird River Greenstone Belt
Syntectonic Intrusive Rocks
Bird River Sill
0
5
10km
Bird Lake
Bird River
Highway
Bernic Lake
Lac du Bonnet
River
Winnipeg

FIGURE 9.—Generalized geology of the Bird River greenstone belt, southeastern Manitoba, showing the disposition of the Bird River Sill and its associated mineral occurrences (after Scoates and others, 1986a, fig. A-1). Open circles indicate nickel-copper deposits; open squares, chromite deposits; open triangles, platinum-group elements.

TABLE 3.—Systematic geologic surveys in the Bird River area

Years	Surveys
1898 and 1912	Reconnaissance geologic mapping conucted along main watercourses by the GSC (Tyrrell and Dowling, 1900; Moore 1913).
1920 to 1930	Parts of the area mapped at 1:63,360 scale (1 in.=1 mi) by the GSC (McCann, 1921; Cooke 1922; Wright, 1938).
1948 to 1951	More detailed mapping at 1:31,680 scale (1 in.=5 mi) by the Manitoba Mines Branch (Springer, 1948; Davies, 1952).
1954 to 1956	Parts of the area mapped at 1:12,000 scale (1 in.=1,000 ft) by the Manitoba Mines Branch (Davies, 1955).
1969 to 1971	Bird River Sill in the area of Chrome claims mapped at 1:15,890 scale (1 in.=0.25 mi) and 1:12,000 scale (1 in.=1,000 ft) by the Manitoba Mines Branch (Trueman, 1970, 1971; Trueman and Macek, 1971).

A hypothetical resource assessment study of the Bird River area made in 1915 (T_1, fig. 8), before the discovery of nickel-copper sulfides, would have been based solely on reconnaissance geologic surveys along navigable waterways (Tyrrell and Dowling, 1900; Moore, 1912). Because mafic and ultramafic igneous rocks had not been observed at that time, economic concentrations of nickel-copper, chromite, and PGE would not have been expected to occur. The commodities would have been given a low rating (T_1, fig. 8).

A resource assessment study of the same area, made in 1925 (T_2, fig. 8), would have produced a different result. At this time, nickel-copper sulfides had been discovered in the Maskwa Lake area on the northern limb of the Bird River Sill and in the Bird River area on the southern limb. Exploration (trenching, diamond drilling) was active in the area. In addition, two separate reports illustrating the character of the gabbroic rocks of the sill had been published (Colony, 1920; Cooke, 1922). Ultramafic rocks of the intrusion had still not been identified. The presence of nickel-copper sulfides and additional information concerning the host gabbroic rocks would have produced a high rating for nickel-copper (T_2, fig. 8).

Chromite was discovered in mafic and ultramafic rocks of the Bird River Sill in 1942. By 1943, the essential character of the Bird River Sill and its contained chromite and nickel-copper sulfide deposits was well known (Bateman, 1943). A resource assessment study made by using the 1945 data base (T_3, fig 8) would have resulted in the area's being rated as having a high potential for economic concentrations of chromite in addition to nickel-copper.

The assignment of a favorable potential for concentrations of PGE in the Bird River Sill simply required application of the concept that other layered mafic-ultramfic intrusions besides Bushveld and Stillwater might also host stratiform PGE-bearing layers. This concept has been applied to various layered intrusions in the recent past. A

TABLE 4.—Significant benchmarks in the exploration and mining history of the Bird River area

Year(s)	Event
	Chrome
1935	Chrome values in a sample from the Star claim (later Wards claim) reported by Cominco to prospector John Lupin.
1942	June 25, G. M. Brownell identified chromite at Wards claim. July 7, J. D. Bateman identified chromite at the Page property. July 19, G. M. Brownell, working for Gods Lake Gold Mines, stakes Chrome claims.
	Nickel-copper
1917	Nickel-copper deposits discovered north of Maskwa Lake (Mayville claim).
1917 to 1920	Copper and nickel-copper deposits discovered in the Bird River area (Chance and Devlin deposits).
1920 to 1930	Numerous trenches excavated on the Chance, Devlin, Cup Anderson, Wento, and Diabase claims. In addition, shallow prospect shafts sunk on the Wento and Chance deposits and a few diamond drill holes put down on the Wento, Cup Anderson, Devlin, and Chance deposits (Davies, 1955).
1930 to 1951	Several companies active in the area; 5,700 ft (1,737 m) diamond drilled (Davies, 1955).
1951 to 1953	A further 22,00 ft (6,705 m) of diamond drilling led to estimates of 1,350,000 tons of ore grading 1.15 percent nickel and 0.32 percent copper on the Chance claim to a depth of 500 ft (152 m) (Davies, 1955).
1969 to 1974	Production of copper-nickel ore from the Dumbarton Mine. During this period, 1,539,290 t of ore grading 0.81 percent nickel were mined (Coats and others, 1979).
1974	Discovery of the Maskwa West zone by diamond drilling in May 1974 (Coats and others, 1979).

TABLE 4.—Significant benchmarks in the exploration and mining history of the Bird River area—Continued

Year(s)	Event
1974 to 1976----------------	Production of nickel-copper ore from the Maskwa West open pit. During this period, 365,730 t having an average grade of 1.16 percent nickel and 0.20 percent copper were mined (Coats and others, 1979).

current resource assessment study of the Bird River area using the 1985 data base (T_4, fig. 8) would assign a high rating for PGE.

The historically based resource assessment matrix illustrates how the assessed rating for certain commodities can change with time. Although the area chosen to illustrate this point (the Bird River area) has a well-documented exploration and mining history, any number of areas containing different economically significant commodities could be accepted. Additionally, it would be possible to select areas for which the totoal geoscientific data base has increased significantly with time but for which concentrations of economically significant commodities have not as yet been discovered. In the latter case, the confidence of the assessment increases with time as the overall data base is enhanced.

Areas in northern Canada for which reconnaissance-level geologic maps (1:250,000 scale) form the data base for resource assessment studies are considered to represent T_1 in the historically based resource assessment matrix. The reconnaissance nature of the data base and the remoteness of these areas have resulted in little or no exploration activity. Resource assessment studies of such areas that use available information result in low ratings for many commodities. Additionally, these low ratings are often qualified by low confidence levels.

Brobst and Goudarzi's (1983, p. 7) argument—that final, once-and-for-all assessments of mineral resource potential cannot be made and that periodic reassessment must be made as new data become available—is particularly appropriate for resource assessment studies made in northern Canada. The historically based resource assessment matrix illustrates the importance of time in terms of changing potential ratings for commodities as well as in terms of providing an increasing confidence level for commodity ratings regardless of whether the ratings themselves change with time.

The resource assessment studies of the Wager Bay and Nahanni areas are attempting to resolve this problem by combining more detailed systematic mapping (1:50,000 scale) and surficial geologic studies to enchance the data base before resource assessment statements are made. As a result, assessment statements should be made at T_2, and the confidence level should increase.

SUMMARY

Before 1980, resource assessments were done on an ad hoc, phase 1 (paper research) basis by a number of government departments in response to requests from international bodies (for nationally based commodity studies) and from other government departments (for geographically restricted resource assessments). Personnel were drawn away from regular duties for these assessments. After 1980, MERA committees were established to deal with assessments on a routine basis, and personnel were assigned

TABLE 5.— Thematic studies devoted to various aspects of the Bird River Sill

Year(s)	Study
1920	Detailed examination of gabbro in Maskwa Lake area completed (Colony, 1920). Gabbro compared with Sudbury norite.
1922	Detailed examination of gabbro in Oiseau (Bird) River area completed (Cooke, 1922). Similar characters of Bird River and Maskwa Lake gabbros noted. No mention of ultramafic rocks.
1938	Peridotite in Bird River area first mentioned, although no indication given of its relation to gabbro in the area (Wright, 1938).
1943	Name "Bird River Complex" applied to ultramafic-mafic rocks of the Bird River area (Bateman, 1943). Complex compared with the Stillwater Igneous Complex of Montana and the the Blow-Me-Down Complex of Newfoundland.
1970 to 1971	Detailed mapping of the Chrome and Page properties of the Bird River Sill completed (Trueman, 1970, 1971; Trueman and Macek, 1971). Study of the sulfide deposits associated with Bird River Sill completed (Karup-Moller and Brummer, 1971).
1973	Study of copper-nickel sulfide deposits of Bird River area completed (Juhas, 1973).
1980	Regional assessmemt of Bird River greenstone belt emphasized its stratigraphy and structure (Trueman, 1980).
1983	Preliminary examination of stratigraphy of Ultramafic Series of Bird River Sill made (Scoates, 1983).
1983 to 1986	Studies directed toward documenting occurrence of platinum-group elements in Bird River Sill (Theyer, 1983, 1984, 1985; Scoates and others, 1986b).

specifically to primary resource assessment duties. Phase 2 (hands-on) assessments were made possible by joint funding from three or more government departments. Methodology throughout this time has emphasized qualitative, relative rating schemes derived by applying mineral deposit analogs to geologic domains.

Current GSC resource assessments of the Eastern Arm of Great Slave Lake, northern Baffin Island, and Banks-Victoria Islands are transitional between phase 1 and phase 2 and are in the final stages of completion. Two examples from the Banks-Victoria Islands study area illustrate application of the volcanic red bed copper and sandstone uranium deposit types to two different geologic domains. Phase 2 resource assessments of the Wager Bay and Nahanni River areas are in their second year of fieldwork. Published Phase 1 assessments should be viewed as working models to be tested and improved with each addition to the geologic data base. The phase 2 work is producing such new data in the form of more detailed geologic maps and a variety of geochemical data.

Continuing reassessment is necessitated by the sparse geologic data base available in northern Canada, by changes in ratings, and by the changing confidence in those ratings caused by additions to the geologic data base. These changes can be predicted by comparison with historical analogs. For example, the mineral potential of the Bird River Sill has increased with time because of additions to its geologic data base. These additions permitted the application of additional mineral deposit analogs suggesting greater resource potential of the commodities Ni-Cu and subsequently Cr-PGE. Confidence in the application of these analogs has also increased with time.

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THE ROLLA AND SPRINGFIELD, MISSOURI, CUSMAP RESOURCE ASSESSMENTS[1]

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ABSTRACT

We used the following six-step procedure to appraise the mineral resource potential of the Rolla 1°x2° quadrangle: (1) compilation of mineral occurrence, geologic, geophysical, subsurface lithofacies and structure, and subsurface trace-element geochemical maps of the quadrangle to identify the geologic environments present; (2) determination of mineral deposit types that could reasonably be expected to occur in these environments; (3) development of descriptive models of these deposit types; (4) selection, from each model, of diagnostic and permissive recognition criteria for the occurrence or nonoccurrence of that type of deposit; (5) systematic examination of all data from step 1 for the presence or absence of recognition criteria; and (6) synthesis and evaluation of the areal distribution and relative importance of recognition criteria to appraise the favorability for occurrence of each deposit type.

On the basis of steps 1 and 2, we considered recognition criteria for 1[illegible] types of metallic mineral deposits. Synthesis and evaluation (step 6) successfully "rediscovered" the Viburnum Trend and also identified three new areas considered to have a very high potential for major Mississippi Valley-type deposits in the Bonneterre Formation, four new areas for smaller, similar deposits in post-Bonneterre formations, and three new areas for deposits of Precambrian Kiruna-type iron ores, as well as small areas of high potential for several other, less important types of deposits.

Quantitative modeling and digital (computer-assisted) synthesis done at the EROS Data Center, using the same data base, permitted independent evaluation of the quadrangle's 128,576 individual 400 m^2 cells by the same five diagnostic criteria used in the manual synthesis for Mississippi Valley-type deposits in the Bonneterre Formation. The digital synthesis confirmed the three areas of very high potential and fine tuned them into nine levels of favorability.

In the resource assessment of the Springfield 1°x2° quadrangle, we used the same six-step procedure and a more generalized Mississippi Valley-type model to accommodate a greater diversity of subtypes and a subsurface data base that was less dense in areal coverage (that is, fewer drill holes) but more detailed lithologically. This process divided the quadrangle into 23 blocks of high, moderate, and low potential for Mississippi Valley-type deposits in six different stratigraphic zones.

We conclude that this general assessment method has proved its usefulness and should be applicable in similar geologic terranes anywhere.

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[1] Prepared in cooperation with the Missouri Department of Natural Resources, Division of Geology and Land Survey.

INTRODUCTION

A comprehensive study of the geology and a formal appraisal of the mineral resource potential of the Rolla, Mo., $1^{o}x2^{o}$ quadrangle were conducted jointly from 1975 to 1980 by the U.S. Geological Survey (USGS) and the Missouri Department of Natural Resources, Division of Geology and Land Survey (Missouri Geological Survey), under the aegis of the Conterminous United States Mineral Assessment Program (CUSMAP) (Pratt, 1981). The principal focus of this appraisal was the potential for the occurrence of Mississippi Valley-type deposits—stratabound sulfide ores of lead, zinc, and, locally, other metals, hosted by platform carbonate rocks. The appraisal was based on a qualitative manual synthesis of numerous geologic factors considered to be favorable for this type of deposit. Each geologic criterion included in this synthesis was regarded objectively, but the task of mentally combining the criteria—some of which were expressed graphically as isolated points, some as lines, and some as irregular areas—and evaluating the combinations necessarily required some judgments that were both arbitrary and subjective. Although the team of geologists that made this appraisal was fully satisfied with the validity of its results, we nevertheless felt in retrospect that a more disciplined synthesis, with the aid of a computer, would be worthwhile as both a check on and a refinement of the manual synthesis. The opportunity for a digital synthesis using the same data that had been used originally came in 1982. This report summarizes the methods used in both the manual and the digital syntheses and presents and compares the results. The report concludes with a description of the subsequent CUSMAP assessment of the adjacent Springfield quadrangle in southwestern Missouri, which was undertaken as a logical followup to the Rolla project.

THE ROLLA CUSMAP ASSESSMENT

The Rolla $1^{o}x2^{o}$ quadrangle of southeastern Missouri was selected as a CUSMAP study area because it includes most of the Southeast Missouri lead-zinc mining district and parts of the barite- and iron-ore mining areas. The important base-metal ores of this major district occur in geologic formations that extend in the subsurface for hundreds of miles northeast, north, and west through the midcontinent; hence, it was felt that the Rolla quadrangle could serve as a testing ground for appraisal methods that might be used later throughout the midcontinent and in other regions where similar geologic environments suggest a potential for Mississippi Valley-type deposits. A complete discussion of the resource appraisal of the Rolla quadrangle is available elsewhere (Pratt, 1981).

GEOLOGY AND MINERAL DEPOSITS OF THE ROLLA QUADRANGLE

The principal geologic formations of the Rolla quadrangle are sedimentary rocks, mostly dolomites, of Late Cambrian and Early Ordovician age, which overlie volcanic and granitic rocks of Precambrian (Middle Proterozoic) age (fig. 1). The Precambrian rocks are exposed mainly in the St. Francois Mountains in the eastern part of the quadrangle, where a complex of dominantly rhyolitic ash-flow tuffs is intruded by a composite batholith of biotite and amphibole-biotite granites. The Cambrian and Ordovician rocks generally are flat lying or dip gently away from the St. Francois Mountains; they are fairly well exposed around the flanks of these mountains, but, elsewhere in the quadrangle, they are mantled by thick residual cherty clays. Where the entire section of Upper Cambrian and Lower Ordovician rocks is preserved, mostly in the western part of the quadrangle, its total thickness is about 2,000 ft. It is overlain by younger sedimentary rocks in the extreme northeastern and southeastern parts of the quadrangle.

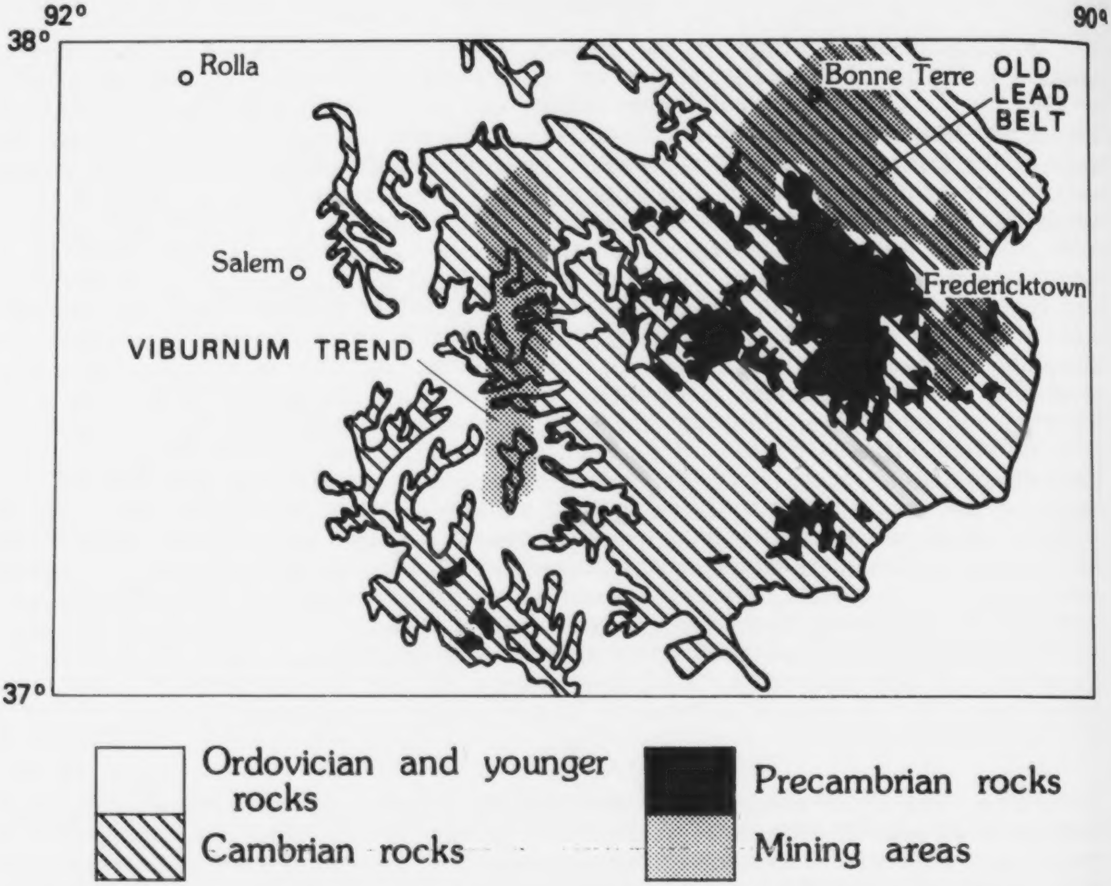

92°
90°
38°
37°
Rolla
Salem
VIBURNUM TREND
Bonne Terre
OLD LEAD BELT
Fredericktown
Ordovician and younger rocks
Cambrian rocks
Precambrian rocks
Mining areas

FIGURE 1.--Generalized geologic map of the Rolla $1^{\circ}x2^{\circ}$ quadrangle of Missouri.

The principal metallic mineral deposits exploited in the quadrangle to date have been Mississippi Valley-type lead-zinc-silver-copper-nickel-cobalt ores in the Bonneterre Formation in the Old Lead Belt and the Viburnum Trend (fig. 1) and Kiruna-type iron ores in Precambrian rhyolites in the St. Francois Mountains. Barite and lead deposits in residual clays, derived by weathering of Mississippi Valley-type deposits in the Cambrian Eminence and Potosi Dolomites, have been of national significance in the past. Several other types of mineral deposits or occurrences are known in the quadrangle but are not pertinent to this report.

METHOD OF RESOURCE APPRAISAL

We developed the following six-step method:

1. We compiled geologic, mineral occurrence, subsurface lithofacies and structure, geochemical, and aeromagnetic and Bouguer gravity maps of the quadrangle to identify the known and inferred geologic environments. In addition to the conventional geologic and geophysical maps, this data base included subsurface lithic-ratio maps showing ratios of sand to shale, limestone to dolomite, and clastic

to carbonate rocks in several of the Cambrian formations, derived from logs of some 1,000 drill holes in the Missouri Geological Survey's extensive library of drill logs; an interpretive map of regional depositional facies of the Bonneterre Formation, also derived from subsurface data; and subsurface trace-element geochemical maps showing zones of anomalously high amounts of base metals in insoluble residues of megascopically "barren" carbonate rocks, derived from spectrographic and chemical analyses of about 11,000 samples representing 10-ft intervals from 62 drill holes.

2. We determined types of mineral deposits that could be expected to occur in the quadrangle on the basis of known worldwide associations of certain mineral deposit types with geologic environments that are present in the quadrangle and mineral deposits and occurrences known to exist in the quadrangle.
3. We developed conceptual descriptive models of these mineral deposit types.
4. We derived "recognition criteria" from each descriptive model for the occurrence or nonoccurrence of that type of mineral deposit.
5. We systematically examined the available data for the existence of the recognition criteria.
6. We evaluated the areal distribution and relative importance of various recognition criteria to appraise the probability of occurrence of each mineral deposit type throughout the quadrangle and also to indicate areas where data are insufficient for a knowledgeable appraisal.

In steps 1 and 2, we identified 17 types of mineral deposits for which the Rolla quadrangle was believed to have some potential. The remainder of this report concerns only the Mississippi Valley-type deposits in the Bonneterre Formation.

Development of Descriptive Model and Selection of Recognition Criteria

Our descriptive model (Pratt, 1981, p. 10-13) was drawn mainly from Snyder (1968), Snyder and Gerdemann (1968), Gerdemann and Myers (1972), and Economic Geology (1977) and was supplemented by discussions with many geologists currently doing research in the area and by our own ideas developed during our studies of the area. The complete model is omitted here owing to lack of space, but it describes the typical deposit in terms of orebody, lithology of host rocks, controlling structures and other features, geochemical and mineral indicators, and geophysical indicators. The recognition criteria discussed below represent essential features of the model that appear to be characteristic of enough known deposits that they can be used as indicators of mineralization.

Recognition Criteria

Geologic parameters that affect the favorability for the presence of a mineral deposit--can be either diagnostic or permissive. Diagnostic criteria are those that are true of all, or nearly all, known deposits and, in most cases, are considered to be required for the presence of a mineral deposit. Conversely, the known absence of such criteria (which is not the same as absence of knowledge of the presence of such criteria) may severely limit or definitively rule out the possibility of the presence of a deposit. Permissive criteria are those that are present in enough known deposits that they can be considered to favor the presence of a deposit, although they are not required; their existence enhances the possibility for occurrence of mineral deposits, especially if diagnostic criteria are presence, but their absence does not diminish the possibility.

From the descriptive model, we defined 12 recognition criteria, 5 of which we consider diagnostic and 7 permissive.

Diagnostic Criteria

Most known deposits are:

1. In dolomite, near the limestone dolomite interface. (Limestone and dolomite are interbedded; "interface" is defined as ls:dol=1:16).
2. In "brown rock" (finely crystalline brown dolomite) near the interface with "white rock" (coarsely recrystallized, white or very light gray, vuggy, illite-bearing dolomite).
3. Near faults and fractures in enclosing or underlying rocks.
4. Near or within favorably situated digitate reef-complex facies.
5. Near areas of anomalously high amounts of base metals in insoluble residues of "barren" Bonneterre Formation (Erickson and others, 1978).

Permissive Criteria

There are seven permissive criteria:

1. A deposit or occurrence of base-metal minerals is known to be present in the Bonneterre Formation or in overlying formations.
2. The overlying Davis Formation is an impermeable shale facies, defined as having ratio of clastic to carbonate rocks greater than 1:16.
3. Subsurface Precambrian knobs are known to be present.
4. Lamotte Sandstone thins or pinches out.
5. The Bonneterre Formation is 200 to 400 ft thick.
6. Insoluble residue of the Bonneterre Formation is more than 50 percent shale (clay).
7. A small, circular pluton of "tin" granite is present in basement.

Manual Synthesis and Evaluation

Using the various maps of the data base as sources, we plotted the areal distribution of each recognition criterion on two base maps; figures 2 and 3 show the diagnostic criteria and the permissive criteria, respectively; both are highly generalized.

Areas of outcropping Precambrian rocks were eliminated as having no potential because the Bonneterre Formation is absent. The extreme northeastern, southeastern, and southwestern parts of the quadrangle can be evaluated only as conditionally favorable because, although the Bonneterre is known to be present, nothing is known about its lithology. By inspecting the distribution of diagnostic criteria, we arbitrarily divided the remainder of the quadrangle into 16 irregular areas (fig. 4) on the basis of various significant combinations of favorable or unfavorable criteria and assigned an objective "score" to each of these areas to compare their relative favorability. For each area, the widespread presence of a recognition criterion was assigned a value of 1, the known absence of that criterion was given a value of -1, and a lack of sufficient data was indicated by 0; the presence of the criterion in only about half of the area was given a value of 0.5. The scores in each area were then summed for both diagnostic and permissive criteria (table 1); by definition, the permissive criteria are considered irrelevant if diagnostic criteria are not present.

Our subjective interpretation of the resource potential indicated by these scores is as follows: (1) large known deposits and areas assumed to be fully explored: areas 1, 2, and 3; (2) very high potential for major undiscovered deposits: areas 4*, 6*, and 9*; (3) low potential: areas 5, 7*, 8*, 10, 11, 12*, 13, 14, 15*, and 16. (Appraisals of areas marked by asterisks could change if additional lithofacies data indicating the presence or absence of certain criteria become available.)

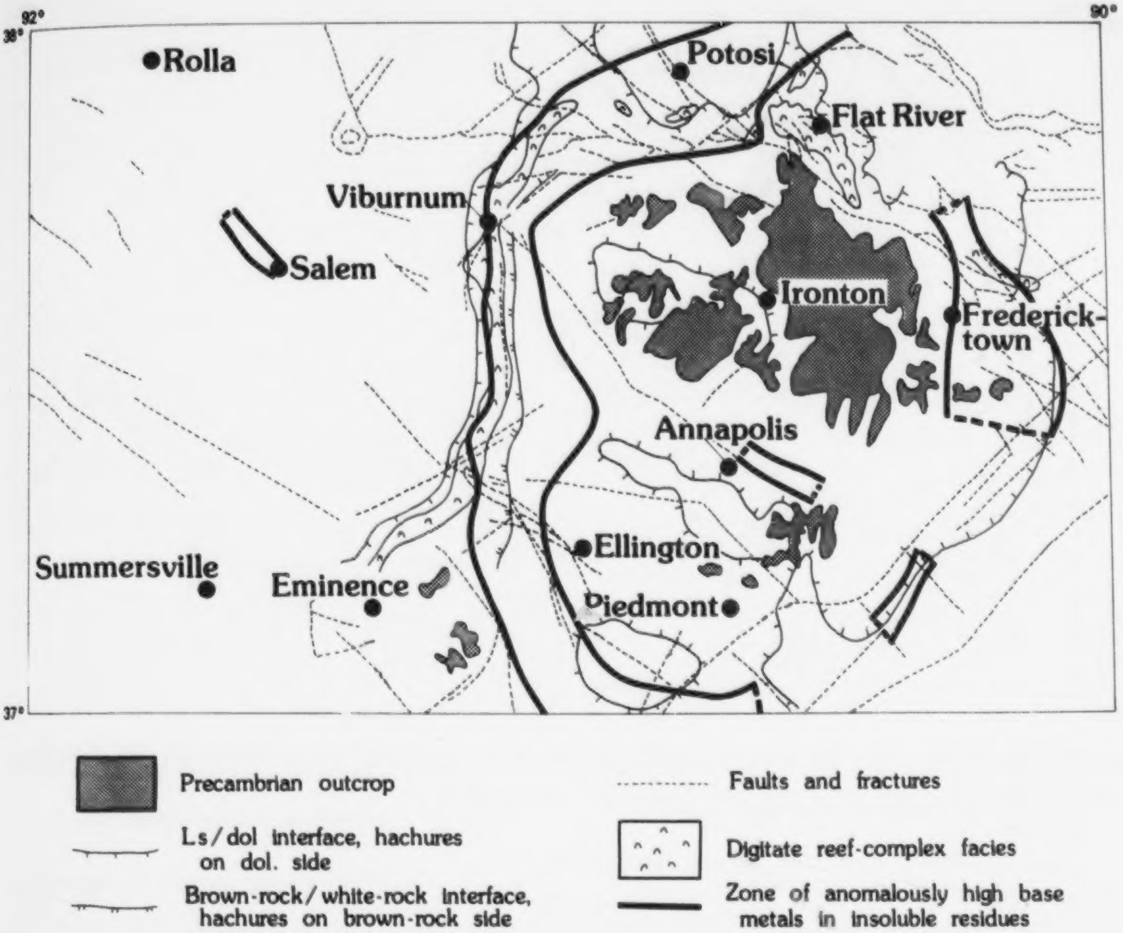

92°
38°
90°
37°
Rolla
Potosi
Flat River
Viburnum
Salem
Ironton
Frederick-town
Annapolis
Ellington
Summersville
Eminence
Piedmont
Precambrian outcrop
Ls/dol interface, hachures on dol. side
Brown-rock/white-rock interface, hachures on brown-rock side
Faults and fractures
Digitate reef-complex facies
Zone of anomalously high base metals in insoluble residues

FIGURE 2.--Diagnostic criteria for the Rolla 1°x2° quadrangle.

Digital Synthesis and Evaluation

As a followup to the Rolla CUSMAP project, a digital geologic data base was developed by members of the Rolla CUSMAP team and members of the USGS's EROS Data Center to define and digitally describe a quantitative geologic model for assessing the Mississippi Valley-type resource potential of the Bonneterre Formation. In general, the study focused on the application of digital data-handling techniques to model the five diagnostic criteria used in the assessment of the Rolla quadrangle. More specifically, the objectives were to quantify the subjective decision rules used in the initial assessment, to apply the resultant model consistently within the quadrangle through digital processing, and, subsequently, to fine tune the previously determined areas of very high potential (table 1, fig. 4) surrounding the St. Francois Mountains.

Data-Base Design and Implementation

For the purpose of this project, the Rolla quadrangle was registered to the Universal Transverse Mercator projection and divided into 400-m^2 grid cells—small

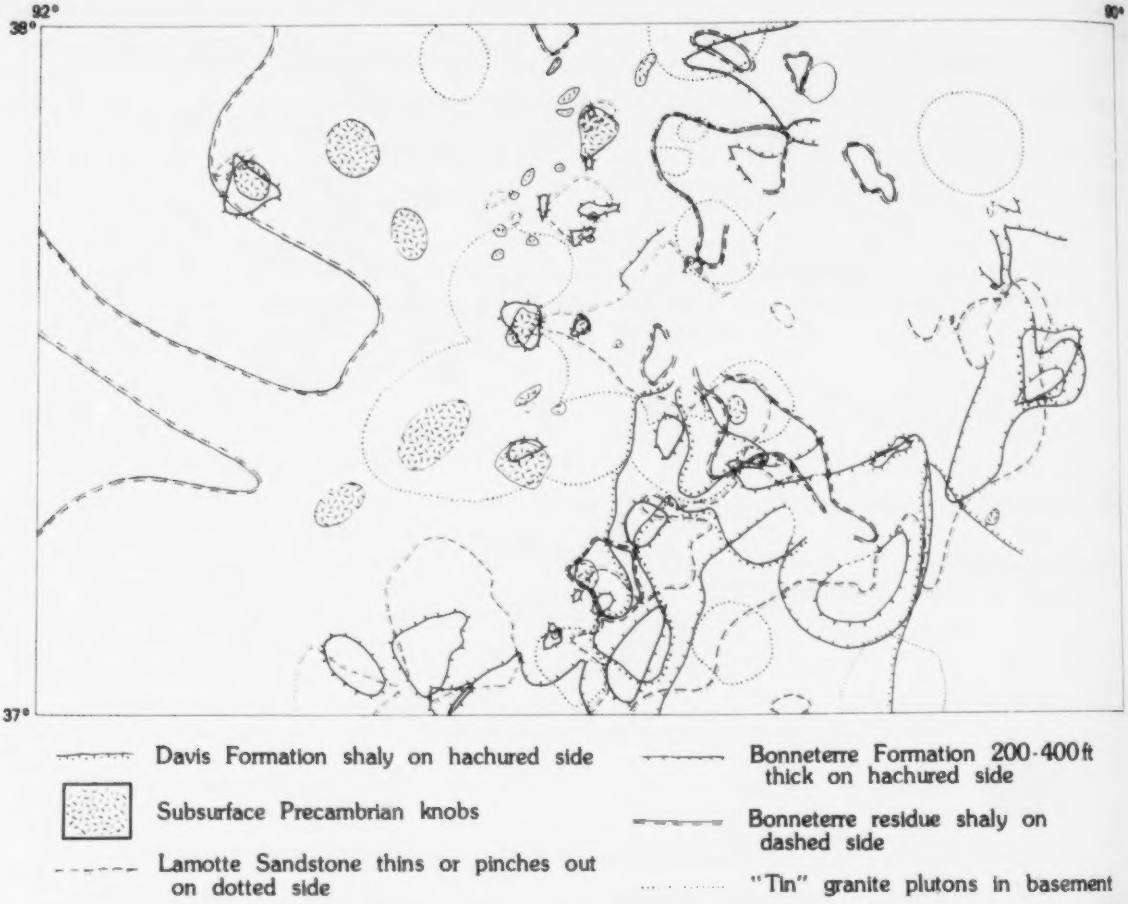

92°
90°
38°
37°
Davis Formation shaly on hachured side
Subsurface Precambrian knobs
Lamotte Sandstone thins or pinches out on dotted side
Bonneterre Formation 200-400 ft thick on hachured side
Bonneterre residue shaly on dashed side
"Tin" granite plutons in basement

FIGURE 3.—Permissive criteria for the Rolla 1°x2° quadrangle.

enough for accurate location of the map data yet large enough to permit computer display of the entire quadrangle grid of 287x448 grid cells at one time (a total of 128,576 grid cells).

The data base was designed to incorporate the diagnostic criteria defined previously. These criteria were subdivided into regional and restricted criteria on the basis of the areal extent of each parameter's availability.

Regional diagnostic criteria (data available for entire quadrangle) include (1) in dolomite, (2) in areas of high base-metal content in "barren" Bonneterre insoluble residues, and (3) near faults and fractures.

Restricted diagnostic criteria (data available for only part of quadrangle) include (1) in "brown rock" and (2) in or near digitate reefs.

Data sets used to define these criteria were digitized as sets of points, lines, and polygons from the same sources used in the manual synthesis. Bonneterre dolomite as defined above was digitized as a set of isopleth lines. Base-metal concentrations in "barren" Bonneterre insoluble residues were digitized as a set of drill-hole points whose concentrations were expressed in terms of anomalous metal feet. (This means of normalizing the analytical data gives the ratio of reported metal content (in parts per

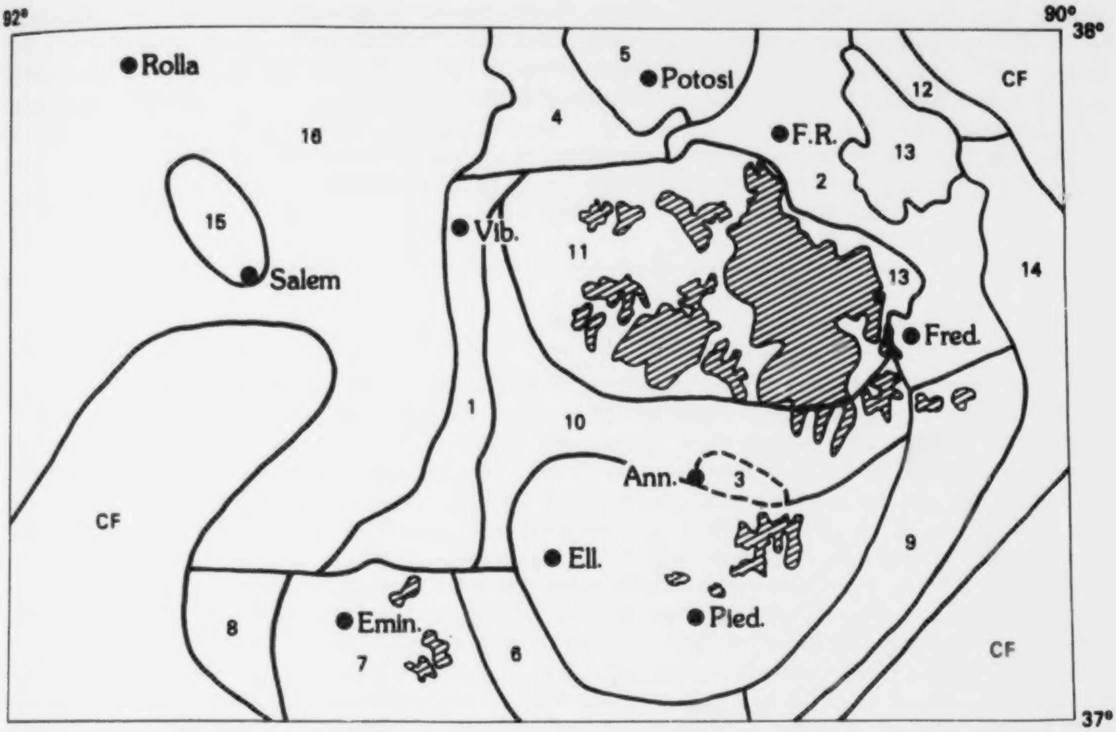


FIGURE 4.--Areas of resource potential for Mississippi Valley-type deposits, Rolla 1°x2° quadrangle (see table 1). Precambrian outcrop areas are hachured. CF indicates conditionally favorable.

million) to a minimum anomalous content established by inspection of the data, multiplied by the thickness of the section (in feet) through which the anomalous content occurs (Erickson and others, 1978).) Faults and fractures were digitized as lines. The Bonneterre brown-rock facies was digitized as a polygon, and its contact with the white-rock facies was digitized as a line. The Bonneterre digitate reef-complex facies was digitized as a set of polygons.

In addition to these primary digitized data sets, several secondary data sets were digitized for use in modeling the diagnostic criteria: a digitized polygon defining the areal extent of available depositional facies data (that is, the outline of the "restricted diagnostic criteria") (G. Kisvarsanyi, 1982); a polygon defining the areal extent of outcropping pre-Bonneterre formations (hence the absence of the Bonneterre) (Thacker and Anderson, 1979); and a digitized set of points defining known occurrences of lead-zinc mineralization in the Bonneterre Formation (Miller, 1982).

Before the digitized variables were modeled, two of the data sets were interpolated by using a minimum curvature algorithm to create continuous arrays. The set of isopleth lines defining the limestone-dolomite ratios was reduced to linear arrays of points (each point having a numerically encoded ratio value) and interpolated to generate a continuous array or surface--the limestone-dolomite ratio surface. The set of points defining the concentrations of base metals in the Bonneterre Formation in anomalous metal feet was also interpolated to create a continuous array or surface--the geochemical surface. In this format, both data sets could be digitally processed to show

TABLE 1.—Sums of scores for diagnostic and permissive criteria for Mississippi Valley-type deposits, Rolla 1°x2° quadrangle

Map area[1]	Criteria	
	Diagnostic	Permissive
1	5	6.5
2	4.5	6.5
3	2	5.5
4	2.5	6.5
5	.5	5.5
6	3	5
7	1	3.5
8	2	0
9	3	5
10	.5	6
11	0	5.5
12	2	1.5
13	1	1.5
14	.5	-2.5
15	0	3
16	-1	3

[1] Numbers correspond to numbers shown in figure 4.

the areal extent of any increment of their respective functions. The final premodel data base contained 11 variables or characteristics for describing the diagnostic criteria, including 9 sets of discrete data (points, lines, and polygons) and 2 sets of continuous data (surfaces).

Quantitative Modeling

In the context of mineral resource assessment, a quantitative model can be considered as a set of mathematical constraints (decision rules) imposed on numerically encoded descriptive parameters for defining a specific type of geologic environment and (or) resource. The manual evaluation used a presence-absence decision rule for diagnostic variables modeled with a manual overlay technique. As described above, the quadrangle was subjectively divided into 19 areas (excluding Precambrian outcrop areas), each of which, except for the three "conditionally favorable" areas having minimum data, was assigned a cumulative score based on the presence or absence of each of the five diagnostic criteria.

The quantitative model applied to the digital geologic data base used the same Boolean logic applied in the manual evaluation; however, to facilitate efficient handling of the numeric scores in the digital domain, five submodels were developed to quantify the five diagnostic criteria. Each submodel was given a range of possible values from 0 to 40. Within this range, 0 represented areas in which the model was not applicable

(Bonneterre Formation absent), 10 represented areas in which the criterion was absent, 20 represented areas in which data for the criterion were not available, and 30 to 40 represented increasing intensity of or proximity to the criterion (table 2). Added together, the five submodels constituted a composite model whose possible score ranged from 0 to 200. This scaling is compatible with processing and display devices requiring a digital range of 0 to 255 (8-bit data). Graphic displays of the digital data and the various submodels and a complete discussion of their development have been given by Pratt and others (1983).

Discussion

The resulting quantitative assessment is shown with respect to known lead-zinc occurrences in figure 5. The regional model (fig. 5, top) incorporated submodels for the three diagnostic criteria (dolomite, geochemistry, and faults) for which data were available for the entire quadrangle and permitted the definition of 12 assessment levels or classes, three of which describe an annular pattern around the St. Francois Mountains that contains all known lead-zinc occurrences in the Bonneterre Formation. The restricted model (fig. 5, bottom) covering only a part of the quadrangle, incorporated submodels for all five diagnostic criteria and led to the definition of 71 assessment levels, 9 of which locally refine the annular pattern and include all known occurrences.

The number of assessment levels achieved by using a digital geologic data base and quantitative modeling techniques was increased sevenfold over the manual assessment. Although the annular "favorable zone" surrounding the St. Francois Mountains was defined in both assessments, the more finely tuned quantitative assessment offered the advantage of setting priorities for a greater number of exploration possibilities. It is important to note that this advantage was realized in a comparison of manual and digital techniques applied to only five diagnostic criteria. When more criteria are used to model mineral resource potential, the task of manually defining significant assessment levels rapidly becomes insurmountable. Consequently, the efficiency and accuracy of consistently applying a geologic model under these circumstances are also lost.

Comparison of Manual and Digital Evaluations

That the digital evaluation would confirm the manual evaluation was foreordained by using the same diagnostic criteria in both models. We believe the principal advantages of the digital evaluation thus far are that (1) demanding a quantitative definition of each criterion (for example, exactly what "near" the brown-rock/white-rock interface means) has forced geologists to reexamine each part of the data base with greater discrimination and (2) being able to handle each criterion independently and in small pieces (400-m^2 cells) has permitted considerable refinement of the manual evaluation in terms of areal definition and ranking of favorable areas. Some users might argue that this degree of refinement is not necessary for the general purpose of resource appraisal in a 1°x2° quadrangle. That contention is probably true, but we believe that, to the extent that such an appraisal might be used for land use evaluation or for a specific purpose such as planning an exploration program, the refinement of the digital evaluation is highly desirable. For any such site-specific uses, however, the refinement is mathematical, not necessarily geological. In all candor, neither the manual nor the digital appraisal can be considered an unqualified success until a discovery of significant mineralization is made in one of the areas appraised to have high potential.

TABLE 2.—Scores assigned to submodels for presence of or proximity to diagnostic criteria

(AMF, anomalous metal feet)

Criterion	Score
Dolomite submodel	
Limestone-dolomite ratio less than 1:16	40
Limestone-dolomite rato greater than 1:16	10
Bonneterre Formation absent	0
Geochemical submodel	
Bonneterre AMF greater than 1,400	40
Bonneterre AMF 500 to 1,399	30
Bonneterre AMF less than 500	10
Bonneterre Formation absent	0
Fault submodel	
Distance to fault less than or equal to 1 km	40
Distance to fault greater than or equal to 1 km	10
Brown-rock submodel	
Distance to white rock less than or equal to 4 km.	40
Distance to white rock greater than 4 to 8 km	38
Distance to white rock greater than 8 to 12 km	36
Distance to white rock greater than 12 to 16 km	34
Distance to white rock greater than 16 to 20 km	32
White rock present	10
Bonneterre Formation absent	0
Digitate-reef submodel	
Digitate reef present	40
Digitate reef more than 0 to 5 km distant	30
Digitate reef more than 5 km distant	10
Bonneterre Formation absent	0

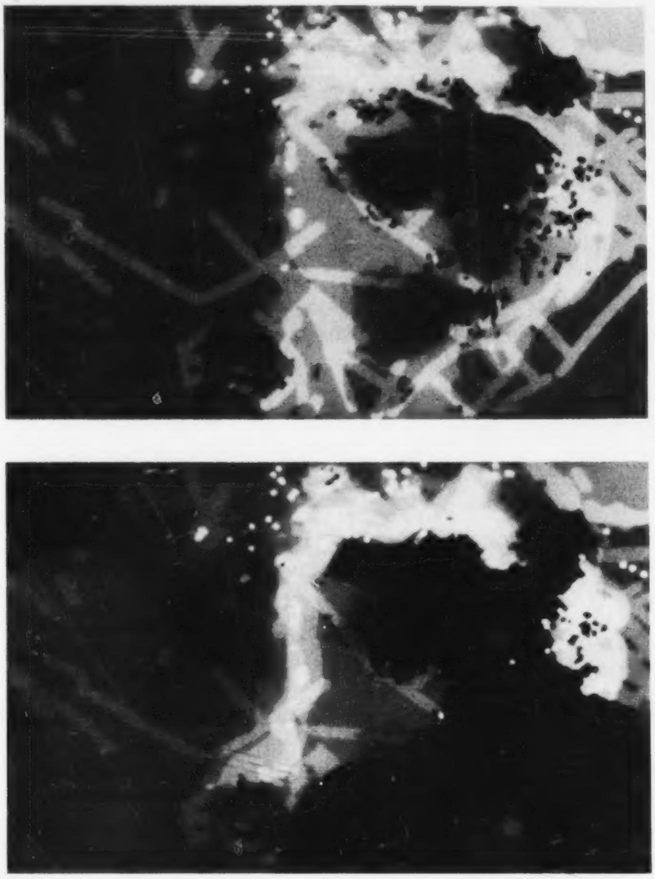


FIGURE 5.—Quantitative assessment of the Rolla 1°x2° quadrangle. Top, Regional model showing three anomalous classes. Classes 110 to 120 are represented by light-gray areas; class 90, medium-gray areas; lead-zinc mines, white dots. Bottom, Restricted model showing nine anomalous classes. Classes 170 to 200 are represented by light-gray areas; classes 120 to 160, medium-gray areas; lead-zinc mines, white dots.

THE SPRINGFIELD CUSMAP ASSESSMENT

Geology and Mineral Deposits of the Springfield Quadrangle

The Springfield 1°x2° quadrangle is in southwestern Missouri, adjacent to the western side of the Rolla quadrangle, and is underlain by nearly flat lying sedimentary rocks of Late Cambrian, Ordovician, Mississippian, and Pennsylvanian ages (fig. 6). Ordovician dolomites underlie the surface of most of the eastern two-thirds of the quadrangle, and Mississippian cherty limestones underlie the western third. Channel sandstones and shallow-water marine sandstones of Pennsylvanian age overlie the Mississippian rocks locally in the western part of the quadrangle.

Economically important Mississippi Valley-type deposits are not known to exist in the Springfield quadrangle. The Central Missouri barite-lead-zinc district is just north of

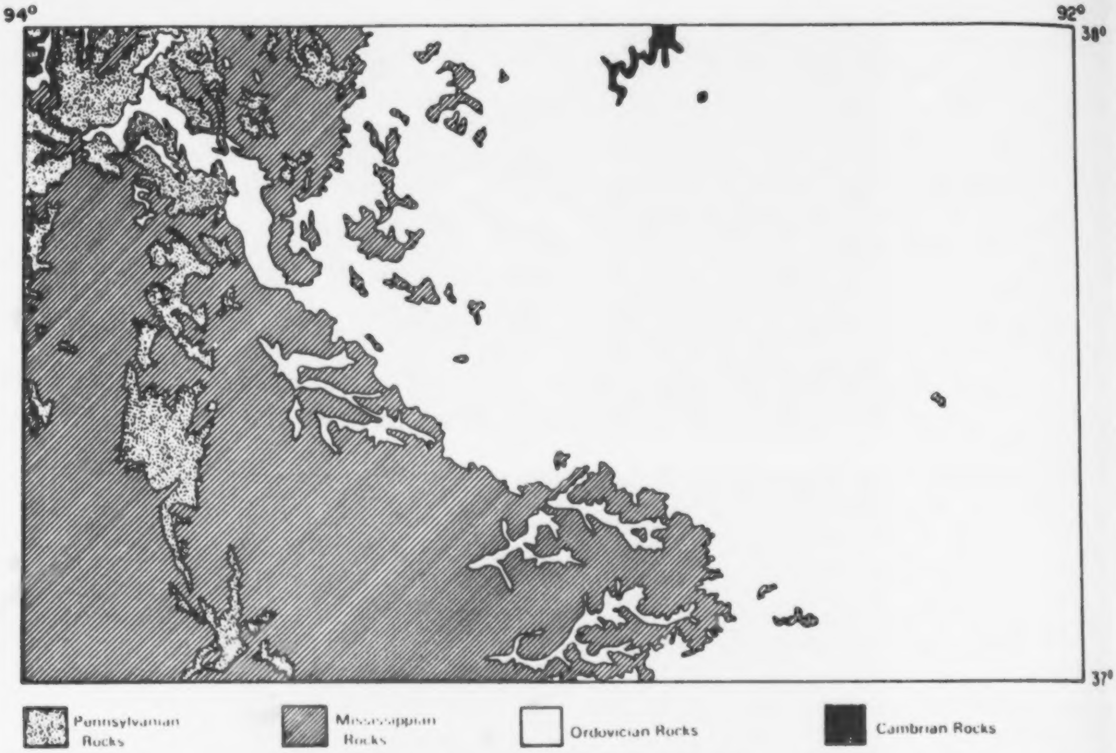


FIGURE 6.—Generalized geologic map, Springfield 1°x2° quadrangle of Missouri (from Middendorf, 1985a).

the quadrangle, and the Mississippian-hosted Tri-State zinc district is centered about 50 km west of the southwestern corner of the quadrangle. The Aurora, Stotts City, and Pierson Creek districts and numerous other small zinc-lead mines and prospects in Ordovician and Mississippian carbonate rocks are present in the western half of the quadrangle, particularly in the southern part (Wharton, 1985). None of the districts in or adjacent to the quadrangle and none of the small mines or prospects within the quadrangle are currently active.

Resource Assessment

The resource assessment for Mississippi Valley-type deposits in the Springfield quadrangle is based on two descriptive models: the Bonneterre-Lamotte model developed for the Rolla quadrangle and a much more generalized model developed in this study for the entire carbonate section above the Cambrian Bonneterre Formation. Erickson and Chazin (1985) have presented a more complete discussion of this assessment.

Models

The Bonneterre Formation is present in the subsurface in the Springfield quadrangle at depths ranging from 1,100 to 1,500 ft. Thus, our appraisal had to consider the potential for the presence of undiscovered Bonneterre-hosted deposits that would be similar to the Southeast Missouri lead-zinc deposits. At present, no Bonneterre-hosted deposits are known in the Springfield quadrangle. The five diagnostic criteria developed for the Rolla quadrangle were considered in this assessment.

Because there are no known economically significant deposits in post-Bonneterre rocks in the quadrangle from which we could derive specific or detailed characteristics, our post-Bonneterre model is necessarily generalized and includes only those characteristics common to most Mississippi Valley-type deposits in the midcontinent region:

1. Deposits in pre-Mississippian rocks are in shallow-water dolomitized carbonate rocks; deposits in Mississippian rocks are chiefly in cherty limestones that are only very locally dolomitized and silicified.
2. Deposits are in or near areas of faults, fractures, and joints. These structures are important because they facilitate fluid movement and, hence, development of solution-collapse breccias, which host some of the best ore in all known Mississippi Valley-type districts.
3. Deposits are in or near areas of anomalously high amounts of base metals in insoluble residues of apparently barren carbonate rocks.

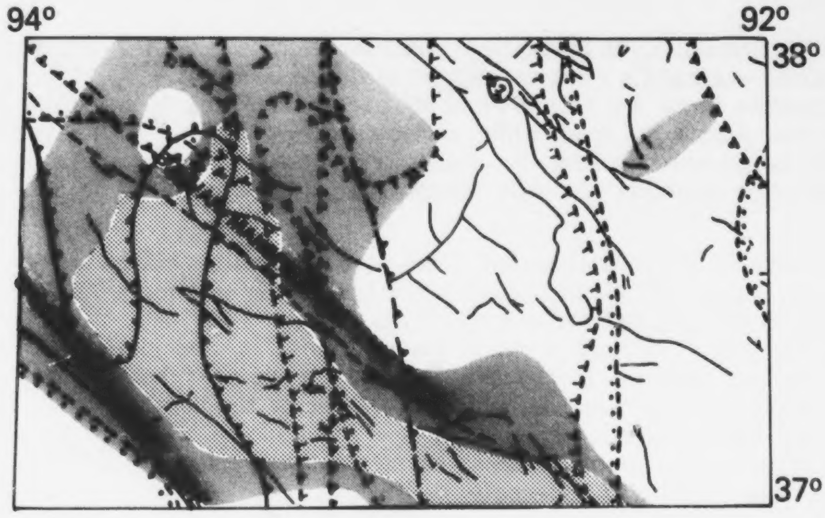
Procedure

The areal evaluation of the quadrangle for resource potential--corresponding to step 6 of the procedure used for the Rolla quadrangle--was made by combining a series of overlay maps showing areal distribution of the three criteria listed above.

Clearly, the first step in making the resource assessment for pre-Mississippian carbonate-hosted Mississippi Valley-type deposits for both models (Bonneterre and post-Bonneterre) was to eliminate areas where dolomite is not present. These areas were eliminated in the Cambrian section by using a series of lithofacies maps prepared for this project by Palmer (in press); the maps show depositional lithofacies at seven levels in the Bonneterre Formation and eight levels in the post-Bonneterre Cambrian rocks. Areas of limestone and of basin, deep ramp, and shelf facies (predominantly clastic rocks) were eliminated from further consideration. Most of the Cambrian facies boundaries have north-south trends and define a broad, gentle platform across the central part of the quadrangle, flanked by ramp and basin facies to the east and west. Elimination of nondolomite areas resulted in a derivative map showing areas of dolomite in the Bonneterre Formation and in the lower half of the post-Bonneterre Cambrian section (figs. 7, 8). The upper half of the post-Bonneterre Cambrian section and the overlying Ordovician rocks are chiefly dolomite throughout the quadrangle. Mississippian carbonates are chiefly cherty limestone and are only very locally dolomitized.

Next, maps showing the structures of the quadrangle (Middendorf, 1985b), the two major Precambrian tectonic zones (E. B. Kisvarsanyi, 1982), and the subsurface geochemical anomalies (Erickson and others, 1985) were combined with the lithofacies map to define areas where dolomite, faults, and anomalously high amounts of metals in insoluble residues of carbonate rocks are all present (fig. 7). On the basis of the distribution of the three criteria as delineated on this map, the quadrangle was divided into 23 areas for the assessment of resource potential (fig. 9). (Because some faults occur in all areas, each area boundary is defined by lithofacies change and (or) anomalous metal values.) Within each of the 23 areas, three different stratigraphic units were considered separately: the Mississippian rocks (where present), the Ordovician rocks, and that portion of the post-Bonneterre Cambrian rocks that consists of dolomite (figs. 7, 8). Each unit was then assigned a resource potential of high, moderate, or low, according to the following definitions:

High potential: Known or suspected presence of dolomite, faults, and more than 5,000 anomalous metal feet in insoluble residues. (The concept of anomalous metal feet



EXPLANATION

DOLOMITE LITHOFACIES AT DIFFERENT STRATIGRAPHIC LEVELS IN POST-BONNETERRE CAMBRIAN ROCKS; COMPARE WITH FIGURE 8.

Note: Upper 50 percent of the post-Bonneterre Cambrian section and the entire Ordovician section is chiefly dolomite throughout the quadrangle.

60 percent level (a 10-foot interval at 60% of the distance from the top of the post-Bonneterre Cambrian to the base). Teeth on dolomite side.

70 percent level. Teeth on dolomite side. East half of the quadrangle is dolomite at this level.

80 percent level. Teeth on dolomite side. Approximately two-thirds of quadrangle is dolomite at this level.

90 percent level. Dots on dolomite side. Dolomite occupies broad north-south belt through central part of quadrangle, and small areas in extreme northwest, southwest, and east-central parts of quadrangle.

BONNETERRE FORMATION. Tick marks on dolomite side. Dolomite is present throughout most of central third of quadrangle.

MAJOR PRECAMBRIAN TECTONIC ZONES--From E. B. Kisvarsanyi (1982).

FAULT--From Middendorf (1985b).

▨ GEOCHEMICALLY ANOMALOUS AREAS--Insoluble-residue samples from each drill hole in stippled area contain >5,000 anomalous metal feet (AMF); in light gray area, 3,000-5,000 AMF.

FIGURE 7.—Diagnostic criteria for the Springfield 1°x2° quadrangle.

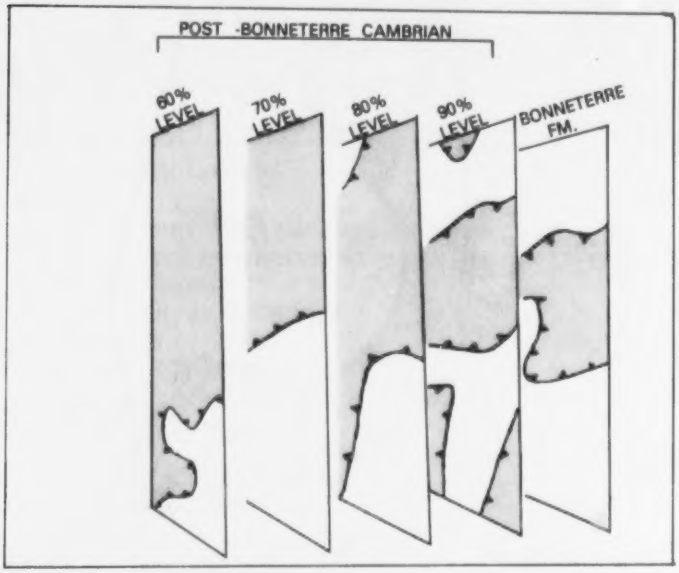


FIGURE 8.—Configuration of the dolomite mass in Cambrian rocks. Shaded areas represent lateral extent of dolomite at each of the five levels shown in figure 7. Connecting the shaded areas vertically would approximate the three-dimensional extent and shape of the dolomitized portion of the Cambrian rocks.

as a measure of the intensity of trace mineralization has been explained by Erickson and others, 1978.)

Moderate potential: Known or suspected presence of dolomite, faults, and 3,000 to 5,000 anomalous metal feet in insoluble residues. An exception is area B-7, which is considered to have moderate potential because a limestone-dolomite interface is present in the Bonneterre-Davis interval; however, the anomalous metal feet values for drill holes in this area are very low.

Low potential: Known or suspected presence of limestone, shale, siltstone, or sandstone; and (or) less than 2,000 anomalous metal feet in insoluble residues.

Individual assessments for each of the areas are given in table 3.

Conclusions

In general, the post-Bonneterre Cambrian rocks have high potential in all A areas and moderate potential in all B areas (except B-7) for large deposits of complex ores of Pb, Zn, Cu, Ni, Co, Mo, and Ag sulfides. The Ordovician and Mississippian rocks, where

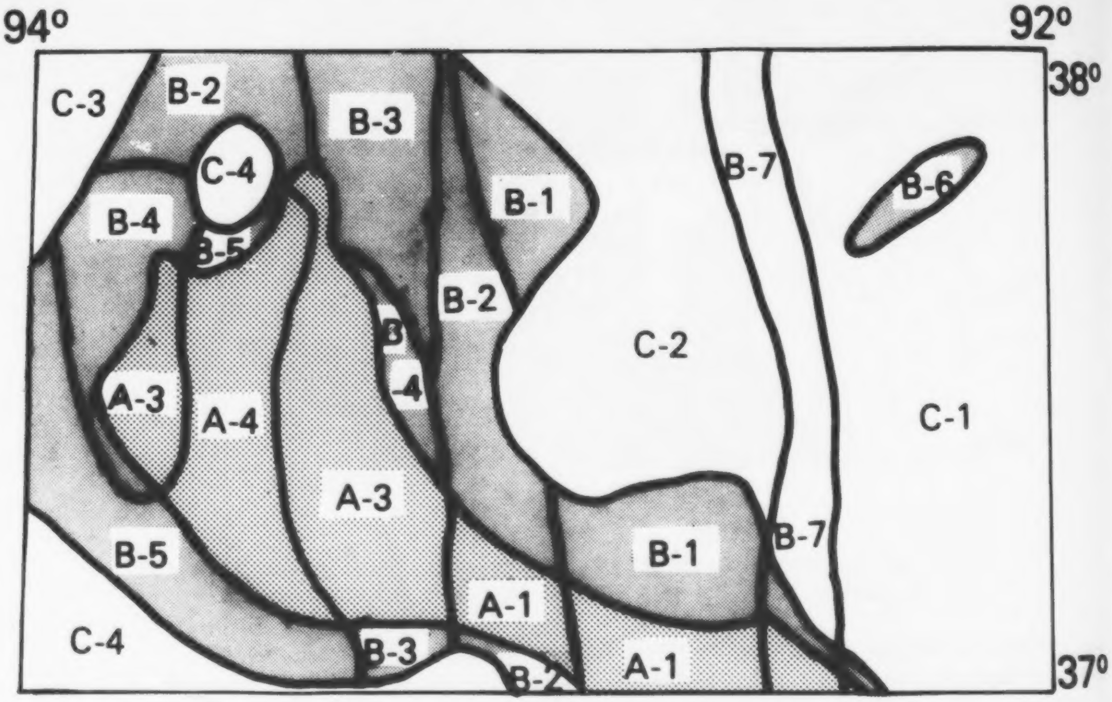


FIGURE 9.—Areas of resource potential in the Springfield 1°x2° quadrangle. Stippling indicates areas of high resource potential; gray areas indicate moderate resource potential.

present, have high potential in all A areas and moderate potential in B areas (except B-7) for small, fault- or fracture-controlled lead-zinc deposits similar to known occurrences in the Springfield quadrangle.

The largest area of high resource potential indicated by our data is a zone in post-Bonneterre Cambrian rocks that extends northwestward across the western part of the quadrangle and southeastward outside the quadrangle to the Missouri-Arkansas border. This possible new mineral trend, bounded by major tectonic zones, was reported by Erickson and others (1981) and has since been expanded by acquisition of lithologic, structural, and geochemical data from additional drill holes (Erickson and others, 1983). The zone contains 17 of the 19 areas in the Springfield quadrangle considered to have high or moderate resource potential. Undoubtedly, new drilling and more closely spaced holes would reveal many barren areas within the postulated trend. Nevertheless, on the basis of the areal distribution of the criteria discussed above, we consider this zone to have moderate to high mineral resource potential. Many of the small inactive surface zinc and (or) lead mines and prospects in Ordovician and Mississippian rocks also occur in this trend. However, none of these occurrences are considered to have high potential for large-tonnage lead-zinc deposits.

GENERAL CONCLUSIONS

We believe that the assessment methodology developed for the Rolla quadrangle proved its usefulness by virtue of its success in "rediscovering" the Old Lead Belt and Viburnum Trend by using geologic data independent of any knowledge of economic

TABLE 3.--Areas of resource potential for Mississippi Valley-type deposits in the Springfield quadrangle

(Pbc, post-Bonneterre Cambrian. 70-percent level, 70 percent of the distance from top of Pbc to base)

Area	Permissive stratigraphic intervals	Potential
A-1--------	Upper 90 percent of Pbc	High
	Ordovician	High
A-2--------	Upper 90 percent of Pbc except for a 10-ft (or thicker) interval at 70-percent level.	High
	Ordovician and Mississippian	High
A-3--------	Upper 60 percent of Pbc	High
	Ordovician and Mississippian	High
A-4--------	Upper 50 percent of Pbc	High
	Ordovician and Mississippian	High
B-1--------	Upper 90 percent of Pbc	Moderate
	Ordovician	Moderate
B-2--------	Upper 90 percent of Pbc except for a 10-ft (or thicker) interval at 70-percent level.	Moderate
	Ordovician	Moderate
B-3--------	In southern block, upper 60 percent of Pbc; in northern block, upper 80 percent of Pbc except for a 10-ft (or thicker) interval at 70-percent level.	Moderate
	Ordovician	Moderate
B-4--------	Upper 60 percent of Pbc	Moderate
	Ordovician and Mississippian	Moderate
B-5--------	Upper 50 percent of Pbc	Moderate
	Ordovician and Mississippian	Moderate
B-6--------	Upper 80 percent of Pbc	Moderate
B-7--------	Bonneterre and Davis Formations	Moderate
C-1--------	Pbc and Ordovician	Low
C-2--------	Cambrian and Ordovician	Low
C-3--------	Pbc, Ordovician, and Mississippian	Unknown
C-4--------	Pbc	Low
	Ordovician and Mississippian	Moderate

mineralization. The assessment of the Springfield quadrangle demonstrated that the same procedure, appropriately modified, can be applied to a different area. However, the validity of the resource assessment itself—that is, the relative potential for the existence of undiscovered mineral deposits in designated areas—cannot be determined on the basis of data currently available. We do believe that the technique of combining maps depicting zones of anomalous metals in insoluble residues of carbonate rocks with maps showing distribution of pertinent carbonate lithofacies and bedrock structure, which we developed in the Rolla project and extended in the Springfield project, is a new approach to both resource assessment and definition of prospecting targets in subsurface carbonate terranes and should be applicable in similar geologic terranes anywhere.

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STUDY OF MINERAL RESOURCE POTENTIAL IN THE BATHURST INLET AREA, NORTHWEST TERRITORIES, CANADA

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ABSTRACT

Geological Survey of Canada assessments of mineral resource potential included one of an area around Bathurst Inlet (lat 66°-68° N., long 106°-110° W.) on the mainland Arctic coast, which included a proposed large national park. This study in an area lacking detailed geologic mapping is noteworthy because it demonstrated that resource assessments would be considered as part of the newly established procedures for evaluating parkland proposals. The valuation was begun in 1980 as a priority subproject of a continuing regional metallogenic study of the northwestern part of the Canadian Shield and was completed by submission of a preliminary report to an interdepartmental committee in early 1983 and a final report made available to the public in 1984.

Part I of the study outlines the metallogeny of the region (that is, the ways that known and yet undiscovered deposits may have been formed in various locales during successive geologic events). Part II focuses on mineral prospects and exploration possibilities within different sectors of the proposed park area. Part III treats "exploration favorability" throughout the greater Bathurst Inlet area qualitatively on a cell-by-cell basis. Because some metallogenic domains were restricted to the park area and some overlapped others therein, cells within and astride the proposed park boundaries have relatively high ratings in comparison with those in the greater part of the region.

Detailed geologic mapping and other surveys were recommended to test ideas that led to the presumption of relatively high mineral potential. Although these studies have not been carried out, the park decision has been deferred, and it has been acknowledged that any park established in the region should not include any areas of high mineral potential. Intensive prospecting for gold in iron formations was carried out during 1984 and 1985 within and near the original proposed park boundaries.

INTRODUCTION

The Geological Survey of Canada (GSC) assessment of the mineral resource potential of the Bathurst Inlet area, which encompassed the area of a proposed national park, was undertaken in 1980, shortly after the introduction of a new policy stipulating that "inventories" of mineral and fuel resource potential be made before lands were set aside for parks. A preliminary (Phase I) report on the resource potential of the proposed park area was submitted to an interdepartmental committee in early 1983, and a final report was made available to the public in 1984 (Roscoe, 1984).

Normally, Phase I reports are based only on information in available publications and office files. The interdepartmental committee may find that Phase II special field studies and surveys are required before land withdrawal decisions are made. The proposed Bathurst Park, however, was within a region that was already the subject of field-based metallogenic studies, so the Phase I assessment of potential resources in the proposed park area benefited from field studies of mineral prospects and relevant metallotects. Combinations of perceived mineral exploration opportunities within the designated area suggested that the mineral resource potential of the area should be considered higher than that of surrounding areas or most parts of the region as a whole. Various types of technical surveys to test some of these perceptions were suggested in the Phase I report. Because the park decision has been deferred, no special Phase II studies have been mounted, but the GSC has continued independently planned geologic mapping and special projects near and partly within the park study area. Most importantly, mining companies carried out intensive prospecting for gold during 1984 and 1985, also partly within the proposed park area.

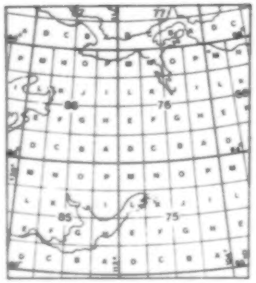
This paper outlines the procedures adopted in the Bathurst Inlet resource assessment. The varied geology and character of scattered mineral prospects through the extensive area, the paucity of detailed geologic information, the lack of extensive coherent geochemical and geophysical exploration surveys, and the inadequacies of prospecting activities in most sectors limited the assessment to metallogenic considerations (conceptions of the types of significant deposits that might have been formed in addition to known prospects during the geologic evolution of the study area).

BATHURST INLET RESOURCE STUDY AREA

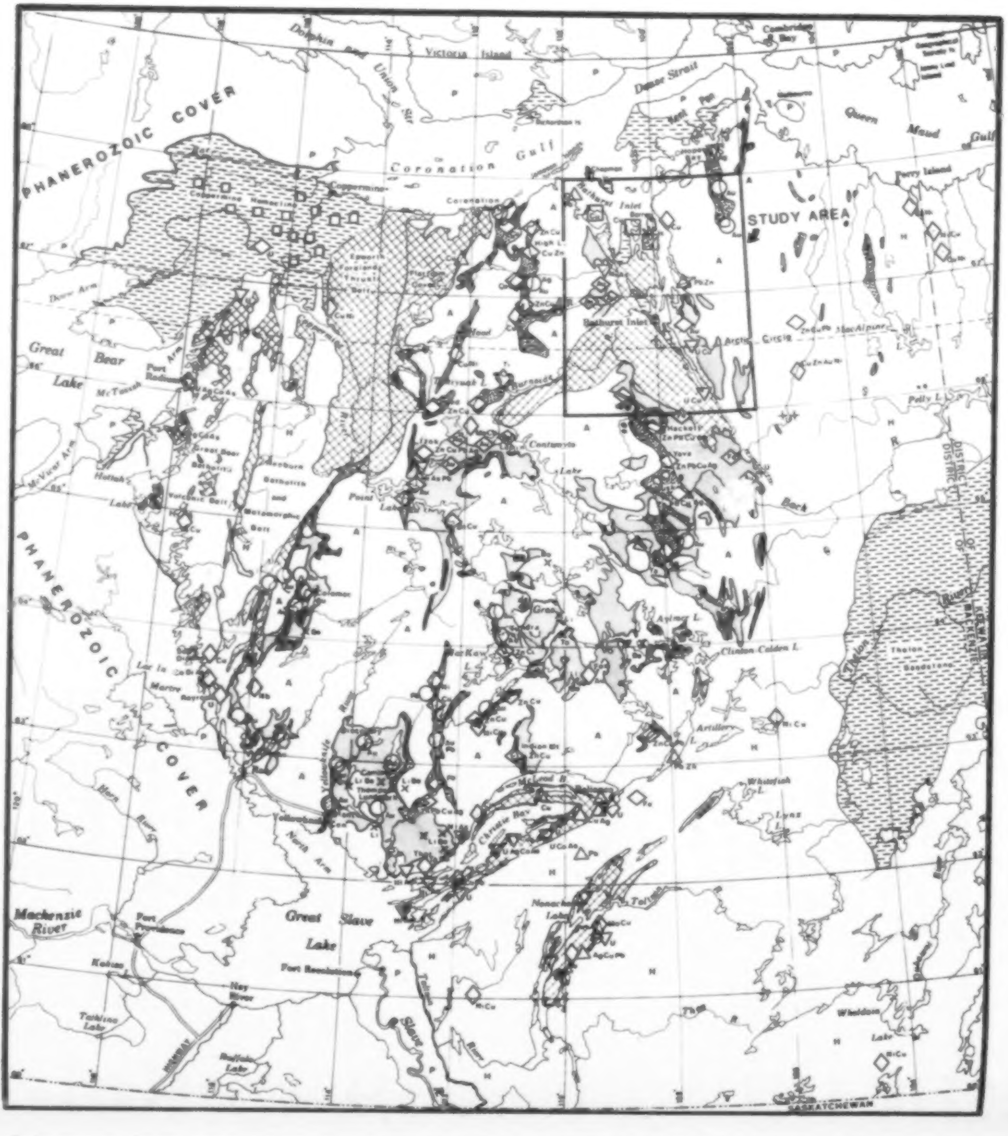
Bathurst Inlet is a major embayment on the northern coast of the Northwest Territories about 900 km north of Yellowknife, the Territorial capital. The inlet, which has numerous islands and an irregular shoreline, extends nearly 200 km south from Coronation Gulf. The proposed park would have consisted of an essential core area covering the entire inlet and adjacent shore areas plus desired additional areas, together totaling about 20,000 km^2 between lat 66° and 68° N. and long 106°38' and 109°22' W. This area was a large part of NTS blocks 76J, 76K, 76N, and 76O, which comprise the Bathurst Inlet resource study area (fig. 1).

The area has many scenic attractions: sea cliffs, high hills, river gorges, and waterfalls. It hosts perhaps as great a variety of plant and animal life as can be found anywhere in tundra areas. Small herds of muskox can be seen frequently, and the huge Bathurst caribou herd migrates through southern parts of the area. The inlet figures in the history of European arctic exploration, scientific investigations, law enforcement, whaling, and fur trading. There is a small Inuit community, Umingmaktuk, along the eastern shore of the northern part of the inlet. A few Inuit families also live at the delta of the Burnside River, the site of a former trading post, mission, radio station, and police post. Bathurst Inlet Lodge at this site currently serves as a base for nature tours and a terminus for canoe trips down the Burnside River and several other barren land rivers that empty into the inlet.

Native copper occurs in basalts on the outer islands of the inlet, and fragments of copper collected on beaches were long used by the Inuit. Soapstone for carving was also obtained in the same area. Galena veins were discovered at the northwestern entry to the inlet by John Richardson of the 1824 Franklin expedition. Several gold, base-metal, and uranium prospects have been found in the area in recent decades, and, in the early 1970's, two small veins of native silver were mined in NTS 77A, just north of the northeastern corner of the study area. About 40 mineral occurrences are recorded in Department of Indian Affairs and Northern Development (DIAND) assessment files and other records. Half of these occurrences are within the designated essential core area of the proposed park. There are no measured potential mineral resources within the study area. Large tonnages of potential base- and precious-metal ores have been outlined, however, a few kilometers south of the southern boundary of the study area in the Hackett River area (76F/16), farther south along the same volcanic belt, 30 km west of the area at High Lake, and 60 to 135 km southwest in the Contwoyto-Izok-Takiyuak Lakes areas. Lupin Gold Mine at Contwoyto Lake has been operating since 1982, using a winter road from Yellowknife and heavy air transport and is currently one of the most



N.T.S. reference grid


PHANEROZOIC COVER
Victoria Island
Dolphin and Union Str
Coronation Gulf
Dease Strait
Cambridge Bay
Queen Maud Gulf
Perry Island
STUDY AREA
Bathurst Inlet
Arctic Circle
MacAlpine L.
Pelly L.
Back
DISTRICT OF KEEWATIN
DISTRICT OF MACKENZIE
Thelon River
Thelon Sandstone
Coppermine
Coronation
Contwoyto Lake
Point Lake
Great Bear Lake
Port Radium
McTavish Arm
Dease Arm
McVicar Arm
Hottah Lake
Lac la Martre
Aylmer L.
Clinton-Colden L.
Artillery L.
Whitefish L.
Lynx L.
Yellowknife
North Arm
Christie Bay
Nonacho Lake
Taltson
Great Slave Lake
Fort Resolution
Mackenzie River
Fort Providence
Kakisa
Tathlina Lake
Hay River
Buffalo Lake
Slave River
Wholdaia
SASKATCHEWAN

LEGEND

- ▨ Helikian strata
- ▨ Aphebian strata, minor intrusions
- ☐ Archean metasedimentary rocks
- ▩ Archean metavolcanic rocks
- ☐ P - Phanerozoic cover
  - H - Aphebian igneous and metamorphic rocks
  - R - Rocks (mainly Archean) metamorphosed in Aphebian time
  - A - Archean granitoid rocks and gneisses

MINERAL DEPOSIT SYMBOLS

- ◇ Stratabound
- ◇ Disseminations and stockworks
- ○ Veins, quartz-carbonate with precious metals
- △ Veins, base metal sulphides
- □ Veins and disseminations of native copper, and copper sulphide
- ▽ Veins, pitchblende, chalcocite, arsenides and native copper
- x Pegmatitic deposits
- ✦ Other

Ag - Silver	Li - Lithium
As - Arsenic	Mo - Molybdenum
Au - Gold	Nb - Niobium
Be - Beryllium	Ni - Nickel
Bi - Bismuth	Pb - Lead
Co - Cobalt	Ta - Tantalum
Cu - Copper	U - Uranium
Fe - Iron	Zn - Zinc

0 100 200km

Geology derived from maps and reports of the Geological Survey of Canada and mineral deposit data from files of Department of Indian and Northern Affairs. Compiled by S.M.Roscoe and A.D.Taylor 1981 profitable mines in Canada. It has been widely believed, however, that major mining developments in the region, particularly base-metal mining requiring transport of bulk product as well as supplies, would likely be contingent on the development of arctic shipping and roads from deposits to the coast. Bathurst Inlet appears to afford the best choices for terminals of such roads. Figure 2 shows possible alternative service road routes envisaged in a preliminary study by DIAND.

Data available for this study included records of mineral exploration activities in files maintained by the DIAND Resident Geologist's Office in Yellowknife, published geologic maps and reports, conversations with authors, and field observations made in the area over a few days each field season between 1977 and 1983. The geology and distribution of mineral prospects were compiled on a scale of 1:250,000. Large parts of the area, however, had been mapped only during a helicopter reconnaissance (Fraser, 1964), and the distribution of major classes of Archean rocks (metavolcanic, metasedimentary, gneissic, and felsic intrusive) could be shown only approximately. The distribution of Proterozoic formations was better established by Campbell and Cecile (1975, 1976, 1981) and Campbell (1978, 1979). Their manuscript maps on a 1:250,000 scale and their published map on a 1:500,000 scale (Campbell and Cecile, 1976) were main sources for the compilation of Proterozoic geology on the map accompanying the Bathurst resource assessment report.

Other available information included aeromagnetic maps, aeroradiometric profiles at wide line spacing, and a regional gravimetric survey produced by government agencies. No extensive geochemical surveys have been done, although several companies have done some geochemical surveys of lake-bottom sediment within limited parts of the study area. These surveys were mainly for uranium, but base metals were considered of interest in one. Private companies also flew various airborne geophysical surveys (mainly radiometric) in parts of the area and carried out followup ground surveys. Most of these data were available at least for perusal during preparation of the report, but, with the exception of the regionally coherent aeromagnetic surveys and property assessment reports, few were used or useful for the resource assessment. The magnetometer maps were useful in interpreting outlines of some intrusive rocks.

FORMAT OF RESOURCE ASSESSMENT REPORT

Part I of the Bathurst Inlet study outlines the metallogeny of the Archean Slave structural province and peripheral belts of superjacent Proterozoic strata (fig. 1), with special reference to the study area (NTS 76J,76K,76N, and 76O) and also to other similar Archean and Proterozoic areas. The report analyzes the geologic history of the region and the ways in which known and yet undiscovered mineral deposits may have been formed during successive geologic events. Examples are given of important ore deposits or potential ore deposits near the study area, within the region, or elsewhere whose formation was evidently related to processes that could well have occurred in some places within the study area. A comparable exercise would be going through a list of conceptual models for the formation of all those types of ore deposits that might be hosted in rocks (from oldest to youngest) comparable to those near Bathurst Inlet. Prospects and minor ore mineral occurrences are cited as support for postulates that metals were transported and deposited in the course of specific geologic events and that

◀ FIGURE 1.—Metallogenic domains and variations in mineral potential. Cells are rated from 1 to 10 on the basis of combinations of favorabilities for deposit types, weighted according to probable exploration priorities.

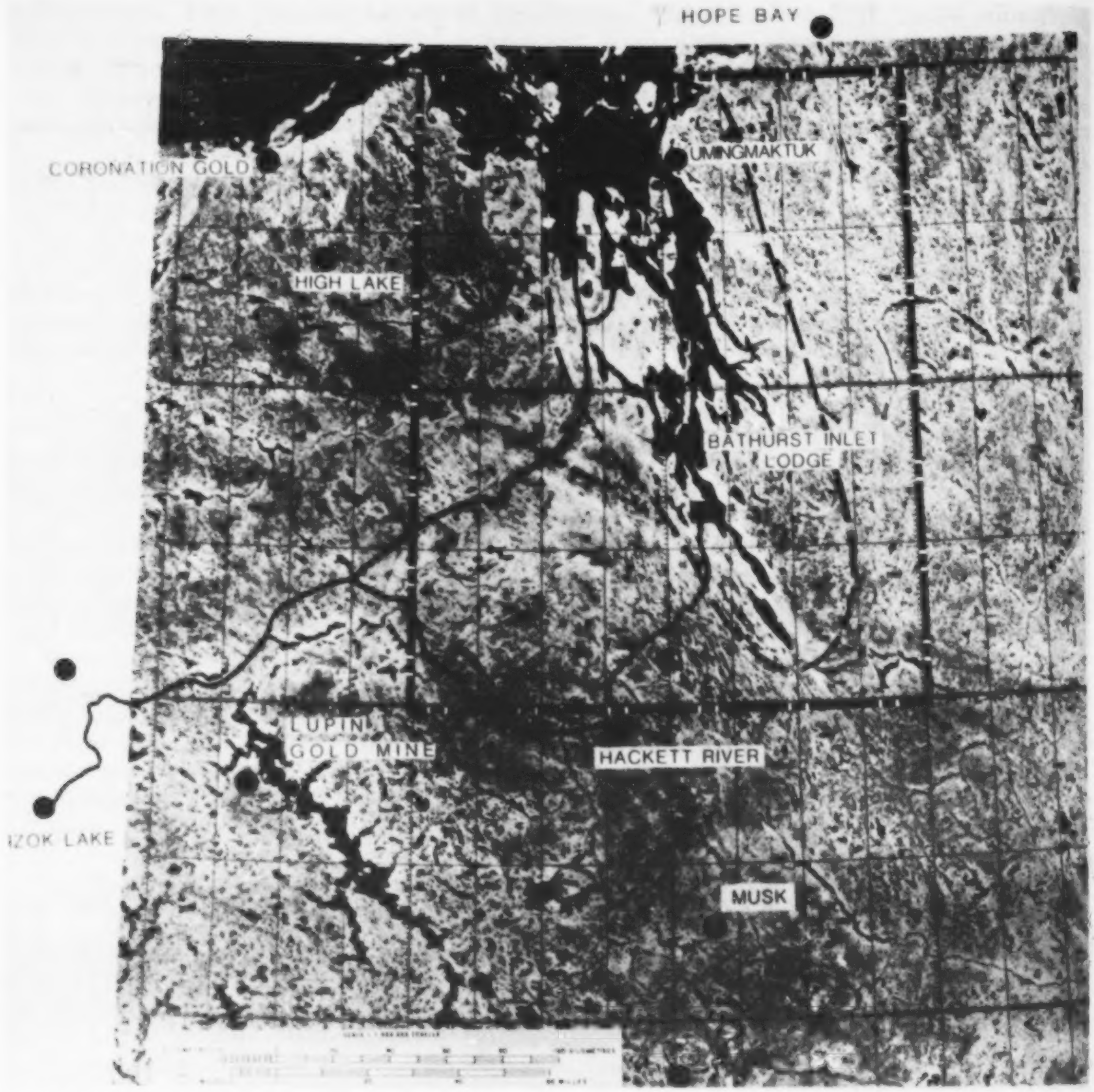


FIGURE 2.--Possible alternative resource service-road routes (solid lines) in the Bathurst Inlet area of Canada, from a preliminary survey of possible routes by DIAND. The study area (NTS 76J, 76K, 76M, and 76N) is shown by long dash-short dash lines; the proposed national park area is shown by dashed lines.

ore deposits may have been formed where and if especially favorable hydrologic and host situations existed. Conversely, a lack of known mineral concentrations of some, but perhaps not all, types indicates that some critical elements in the given deposit models may be missing, although it is always possible that conventional prospecting was inadequate or that geochemical surveys might disclose the existence of shallowly buried concentrations.

The outline of regional metallogeny is reasonably complete in terms of geologic history and types of potentially economically significant deposits known in the region or worth seeking in the study area. It was sketched as briefly and simply as possible and unavoidable technical terms were defined at first use. As a result, the study may have been more understandable to people interested in the use of the land, tourists, and prospectors, many of whom would not have seen a resource assessment report previously.

Part II of the report deals more specifically with mineral prospects and exploration possibilities within different sectors of the proposed park area. Twenty types of mineral deposits are identified as known to occur at least in the form of small minor mineral concentrations, as likely to be present, or as possibly present on the basis of geologic features (table 1). Probabilities for discovering each deposit type in the different sectors of the proposed park are discussed and rated qualitatively.

Part III summarizes "exploration favorability" throughout the study area on a cell-by-cell basis for the 64 tertiary NTS blocks 15 minutes in latitude by 30 minutes in longitude (26 km by approximately 22 km). Possibilities for discovering significant deposits of 16 different types were rated qualitatively (negligible, low, moderate, or high) and tabulated (table 2). Cells within or partly within the proposed park area are identified in the table. Five major metallogenic domains are recognized within the area on the basis of geology and known mineral occurrences. The combinations of favorabilities for the different deposit types ascribed to each cell reflect its position within one of these domains or in some cases astride boundaries between domains (fig. 1). The cells are rated on a scale of 1 to 10 on the basis of these combinations of favorabilities weighted qualitatively according to the priorities that exploration geologists would probably ascribe to the various types of deposits as exploration targets. Possibilities for discovering volcanogenic massive sulfide deposits, gold deposits in iron-formation, unconformity-related uranium deposits, and high-grade copper deposits contributed most to the ratings of the highest rated cells.

METALLOGENY

Archean metavolcanic rocks prospective for, most importantly, volcanogenic massive sulfide deposits and gold deposits in major vein systems are present in (1) the James River, Hood River, and other belts not far west and southwest of the study area, (2) the Hackett River belt, which extends northward into the southern part of the area, and (3) the Hope Bay belt 50 km east of Bathurst Inlet (fig. 1). Parts of the Hope Bay belt were considered to have very high potential for base-metal and gold deposits because of known prospects, abundant felsic and fragmental volcanic rocks, subvolcanic intrusions, intercalations of a variety of metasedimentary rocks, carbonate alteration, fault zones, and geophysical conductors. Initial exploration of the base-metal prospects, however, was unexpectedly inconclusive, so it is possible that the belt was somewhat overrated.

Extensive areas of turbiditic metasedimentary rocks both east and west of the inlet contain lenses of iron-formation having sulfidic phases, arsenopyrite, and gold concentrations similar to the ore at Lupin Mine and numerous prospects nearby in the Contwoyto Lake area. There had been little prospecting for iron-formation-hosted gold deposits before publication of the Bathurst resource assessment suggesting that the iron-formations were likely to be much more extensive than anyone had realized. Subsequent geologic mapping by the GSC and exploration in 1984 and 1985, which is expected to continue in 1986, have confirmed this suggestion. The proposed park included an extensive area of Archean metasedimentary rocks east of the inlet. Although it would be possible to design a park core excluding any such favorable areas, a conflict could still arise between the Pistol Lake iron-formation gold prospects west of the inlet in 76N/2 and Wilberforce Falls, a prime scenic attraction on the Hood River. Drilling here in 1985 outlined interesting amounts of potential gold ore in the F zone only 1 km west of the river and 5 km upstream from the falls. Other prospects are known even closer to the river and falls.

TABLE 1.--Categorization of mineral deposit types known and suspected in the Bathurst Inlet area

deposit type	code	commodities	NTS blocks with favourable area	
volcanogenic massive sulfide	VMS	Zn,Cu,Pb,Ag	015,16,9,10 K1,2; N6: 08 N2,3	(H) (M) (L)
iron formation - hosted gold	IFG	Au	J1,2*,6*,7*,8,10,11*,14*,15* K14,15; N2,3,6 J9,16; K3,4,12,13; N4,5,12 O3*,4*,5*,6*,11*,13*	(H) (H) (M) (M)
Mafic, ultramafic intrusion - associated deposit	MI	Cu,Ni,PGM Ti,Fe,Cr,V asbestos soapstone	(Ni,Cu) O9; N2 (Ti,Ni) K1,3,4,6,7,12,14,15 (soapstone) N7*,9*,11*,15*,16*	(L) (M) (H)
volcanic associated gold - quartz vein	VGV	Au,W	O15,16,9,10; N2 K1,2; N6	(H) (M)
turbiditic sediment - hosted gold - quartz vein	TGV	Au,W	J2*,6*,7*,11*14*; N2,3,6	(L)
pegmatite - hosted minerals	PM	Li,Ta,Be,Sn Mo,U,REE, Gemstones	K1,2,3,4,6,7,12,13,14,15, N2,3,4,5,6,12,13, J1,2*,6*,8,9,10*,11*,14* J15*,16; O1,2,3*,6*,7,8,9,10 O11*,12*,13*,14,15,16	(M-L) (M-L) (L) (L) (L)
alkalic intrusion - hosted	AI	Ta,Nb,Fe,Cu phosphate,U	K3,4,6,7,12,13,14,15	(L)
unconformity - related deposits uranium, copper, lead-zinc veins;	URU	U	J2*,3*,6*,12*; K16*; N1* J5*,11*,13*; K9*,13*; N8*; O4* J7*,10*,14*; K15*; N2*,6*,	(H) (M) (L)
low sulfur arsenide veins with native silver or pitchblende (associated additionally with intrusive rocks)	URC URL	Cu Pb,(Zn)	N5,6,12; O12* N13; O3*	(L) (L)
	URAS URAU	Ag,(Co,Ni) U,(Co,Ni)	O13*,14; J13*; K15,16*; N2 K1,3,4,5,6,7,11,12,13,14	(LM) (L)
'sandstone' (clastic sediments) interstitial fillings and related veins and replacements of uranium oxide, copper or lead (plus zinc) sulfides, apatite	SIU (SIC) SIL	U (Cu) (Pb,Zn)	J2*,3*,5*,6*,12*; K9*,15 J11*,13*,16*; N1*,8*; O4* J4,10*,14*; K1,3,4,5,6,7,8 K10,11,12,14; N2*,6*,7*; O5*,13*,14	(M) (M-L) (L) (L) (L)
	(SIP)	phosphate	J12*,13*; K16*; N2*	(L)
shale - hosted disseminations of low sulfur copper sulfides, (eg. chalcocite), uranium	SHC	Cu	N2*,6,8*,11	(L)
	SHU	U	N2*,6,8*,11	(L)
carbonate - hosted open space (breccia) fillings and related veins and replacements of zinc-lead sulfides, or low sulfur copper sulfides (eg. chalcocite)	COZ	Zn	J14*; N2*,6,7*,8*,9*,10* N11*,12*,13,14,15*,16*; O5*	(L) (L)
	COC	Cu	J14*; N2*,6,7*,8*,9*,10* N11*,12*,13,14,15*,16*; O5*	(M) (L)
basalt - hosted breccia veins of low sulfur copper sulfides	BXC	Cu	N2*,7*,8*,9*,10*,11*,12,13 N14,15*,16*; O5*,12*	(M) (M)

*indicates favourable area within proposed park boundaries
(H),(M),(L) indicate relatively high, moderate, or low favourabilities, respectively.

TABLE 2.—Types of deposits most likely to be present in individual NTS blocks in the Bathurst Inlet area

(Deposit type codes are given in table 1. H, relatively high favorabilty; M, moderate favorability; L, low favorability. Boldface indicates that a block or deposit is partially or entirely within proposed park area)

NTS block	VMS	IFG	MI	VGV	TGV	PM	AI	URU	URC	URL	URAS URAU	SIU	SIP	SHC SHU	COC COZ	BXC
76J 1		H				L										
(2)		**H**			**L**	**L**		**H**				**M**				
(3)								**H**				**M**				
4												L				
5								**M**				**M**				
(6)		**H**			**L**	**L**		**H**				**M**				
(7)		**H**			**L**	**M-L**										
8		H				L										
9		M				M										
10		**H**				**M**		**L**				**L**				
(11)		**H**			**L**	**L**		**M**				**M-L**				
12								**H**				**M**	**L**			
13								**M**			**L-M**	**M-L**	**L**			
(14)		**H**			**L**	**L**		**L**				**L**			**L**	**L**
(15)		**H**				**M**										
16		M				L										
76K 1	M	L	M	M		M-L					L	L				
2	M	M	L	M	L	M-L					L					
3		L	M		L	M-L	L				L	L				
4		M	M			M-L	L				L	L				
5											L	L				
6			H			M-L	L				M	L				
7	M		M		M	M-L	L				L	L				
8			M					L				L				
9			L					M				M				
10												L				
11			M								L	L				
12		M	M			M-L	L				L	L				
13		L				M-L	L									
14		H	H			M-L	L				L	L				
15		H	M			M-L	L	L			L-M	M				
16			M					H			L-M					
76N 1								**H**				**M**				
2	L	H	L	H		M-L	L	**L**			M	**L**		**L**	**M**	**M**
3	L	H				M-L										

TABLE 2.—Continued

NTS block	VMS	IFG	MI	VGV	TGV	PM	AI	URU	URC	URL	URAS URAU	SIU	SIP	SHC SHU	COC COZ	BXC
4		L				L										
5		M				M-L										
6	M	H	L		L	M-L		L	L	L	L	L				
7		**L**	**L**									**L**			**M**	**M**
8								**M**				**M-L**		**L**	**M**	**M**
9															**M**	**M**
10															**M**	**M**
11									L	L				L	M	M
12						L									M	M
13						M-L				M					M	M
14																M
15			L												**L**	M
16															**L**	**L**
76O 1		L				M										
2		**L**				**L**										
(3)		**L**				**L**				M						
(4)		**L**						**M**		**L**						
(5)		**M**				**L**		**L**				**L**			**M**	**M**
(6)		**M**				**L**										
7		L				L										
8	M			L		L										
9	H		L	H		L										
10	H			H		L										
(11)		**M**				**L**										
(12)		**M**	**M**						**L**						**L**	**M**
(13)		**M**				**L**					L-M	L				
14											L-M	L				
15	H			H												
16	H			H												

Double-struck entry signifies block or deposit possibility partially or entirely within proposed park area.

Numerous granitic pegmatite dikes are present in Archean areas. Until they are investigated, the possibility that some might contain valuable minerals cannot be discounted. Field investigations carried out in conjunction with the mineral resource assessment found some features not recognized during reconnaissance geologic mapping, notably a small area of metavolcanic rocks and an extensive conglomerate formation near the James River in 76N/2 where only metagreywacke had been mapped. Such discoveries invariably are made when more detailed mapping is done in areas where only helicopter reconnaissance mapping had been done previously.

Accordingly, metavolcanic rocks containing volcanogenic massive sulfide deposits could be present in areas mapped as containing Archean rocks other than metavolcanic rocks. Similarly, allowance was made for the possibility that iron-formation-hosted gold deposits might be present in some areas not presently known to contain metasedimentary rocks. An exploration geochemical survey found multielement anomalies in lake-bottom sediments in an area mapped as underlain by Archean metasedimentary rocks. It is possible that the metal sources were volcanogenic massive sulfide-type concentrations in small unmapped areas of metavolcanic rocks.

Some areas of Archean rocks, near gently dipping Proterozoic strata that formerly covered them only short distances above the present erosion surface, could be prospective for root zones of mineral deposits related to unconformities, notably uranium deposits related to sub-Helikian unconformities. This possibility is acknowledged but it is obviously difficult to make much allowance for it in the resource assessment.

Fieldwork initially related to the Bathurst Inlet mineral resource study resulted in the recognition of a large Late Archean or Early Proterozoic anorogenic intrusive complex in the southwestern part of the area. Rocks of this complex, the Booth River intrusive suite (Roscoe, 1984), include layered leuconorite to melanonorite, ilmentite-rich rock, ultramafic rocks, and alkalic perthite granite and may be prospective for a variety of commodities such as platinum-group metals, chromium, titanium, vandium, tin, fluorite, and light metals.

Aphebian (Early Proterozoic) strata on the Goulburn Group, which is about 1.9 Ga, unconformably overlie Archean rocks in a northwest-trending compound graben in Bathurst Inlet and in a synclinorium that trends southwest from the inlet. Minor concentrations of copper and uranium minerals have been found in veins and disseminations in clastic sedimentary rocks, in basalt flows, and in gabbro sills. The strata were deposited under a variety of conditions, including oxidizing and arid conditions attested by salt casts and slump breccias. Their history suggests that they might host significant mineral deposits. The principal types considered in the report are sandstone-hosted uranium, copper and lead deposits formed in favorable redox situations, and carbonate-hosted lead-zinc deposits. The possibilities for uranium deposits were considered most significant, because uranium concentrations occur in a number of interesting prospects.

Helikian (Middle Proterozoic) formations unconformably overlie deformed Goulburn rocks in the northern part of the inlet and in narrow grabens in the southern part. They are remarkably similar to Helikian formations in the Great Bear Lake-Coppermine River region to the west, the Thelon region to the south, and the Athabaska region in Saskatchewan and are considered very likely to host mineral deposits similar to ones in those regions, notably uranium deposits that can be phenomenally rich at the unconformity beneath basal sandstone and conglomerate formations and also various types of copper deposits associated with basalt and adjacent siltstone or dolomite. Numerous occurrences of native copper, chalcocite, bornite, and chalcopyrite confirm the latter possibilities. Inadequately investigated karstic breccias are potential hosts for rich copper deposits as well as perhaps lead-zinc deposits. Almost all occurrences of the Helikian sandstone formation (Ellice Formation) are in fault blocks, so there are very few exposures of the unconformity at its base. Accordingly, the lack of known prospects of unconformity-related uranium deposits is not considered a negative factor. Peculiar concentrations of pitchblende, gold, and selenide minerals in drift at one locality, however, could have been derived from an unconformity deposit, and this factor is considered positive.

The native silver-bearing veins at Hope Bay near the northeastern corner of the area resemble those at Cobalt, Ontario, and are considered to be related to an unconformity as well as to a gabbro sill intruded near the unconformity. Like the Cobalt veins, silver and pitchblende veins at Great Bear Lake, and most unconformity-related uranium deposits, the Hope Bay veins contain arsenide minerals. They are also slightly radioactive. A concentration of niccolite near the James River is probably this type of deposit. Gabbro sheets are intruded near unconformities in several other parts of the area, and the possibility that there may be silver-rich veins in some of these localities cannot be discounted.

DISCUSSION

The approach adopted in this study was essentially a regional metallogenic one aimed at considering probabilities that the mineral deposits of various types contained in the study area and various parts of the proposed park area were more abundant or less abundant than those in other areas. This purely qualitative, almost intuitive approach was indicated by the lack of detailed geologic information available and a dearth of the types of data on geochemistry and mineral occurrences that might be available in well-mapped, thoroughly explored southern mining districts. Accordingly, the study may seem unconventional to those who are accustomed to resource assessment reports that treat abundant numerical data in sophisticated ways and make explicit use of conceptual ore deposit models and grade-tonnage models. The Bathurst Inlet study, nevertheless, did find rational ways of reaching some conclusions about potential resources in an area that included a proposed large national park. Insofar as these conclusions have not been disputed and may have had some influence on a decision to defer establishing such a park, the study may be considered a useful exercise in developing methods of assessing potential mineral resources in remote, little-explored regions.

The study area contains five distinctive metallogenic domains (fig. 3). Few, if any, other areas of equivalent size in northern Canada are likely to contain as many. Each domain contains possibilities for discovering types of deposits that are likely to be potentially exploitable and hence worth seeking. Four of the domains extend into and overlap within the proposed park area. The mineral potential of the Bathurst Inlet area, especially that part of it that had been proposed as a national park, cannot be said to be lower than that of adjacent and nearby areas. Extensive parts of the area are currently being explored for gold deposits, particularly iron-formation-hosted gold deposits.

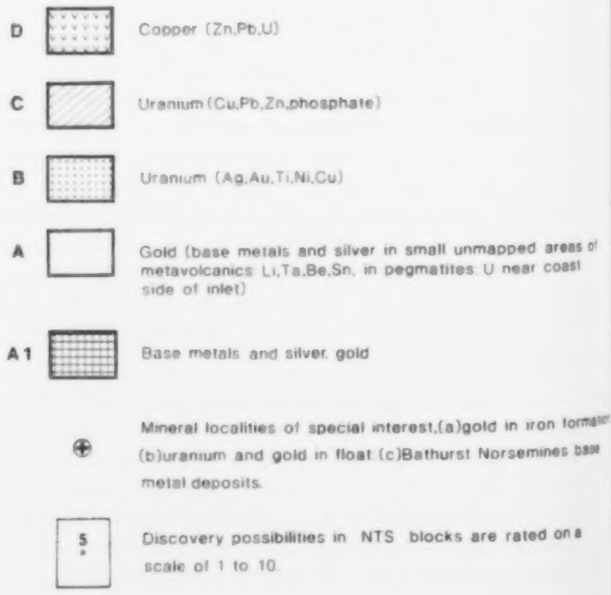
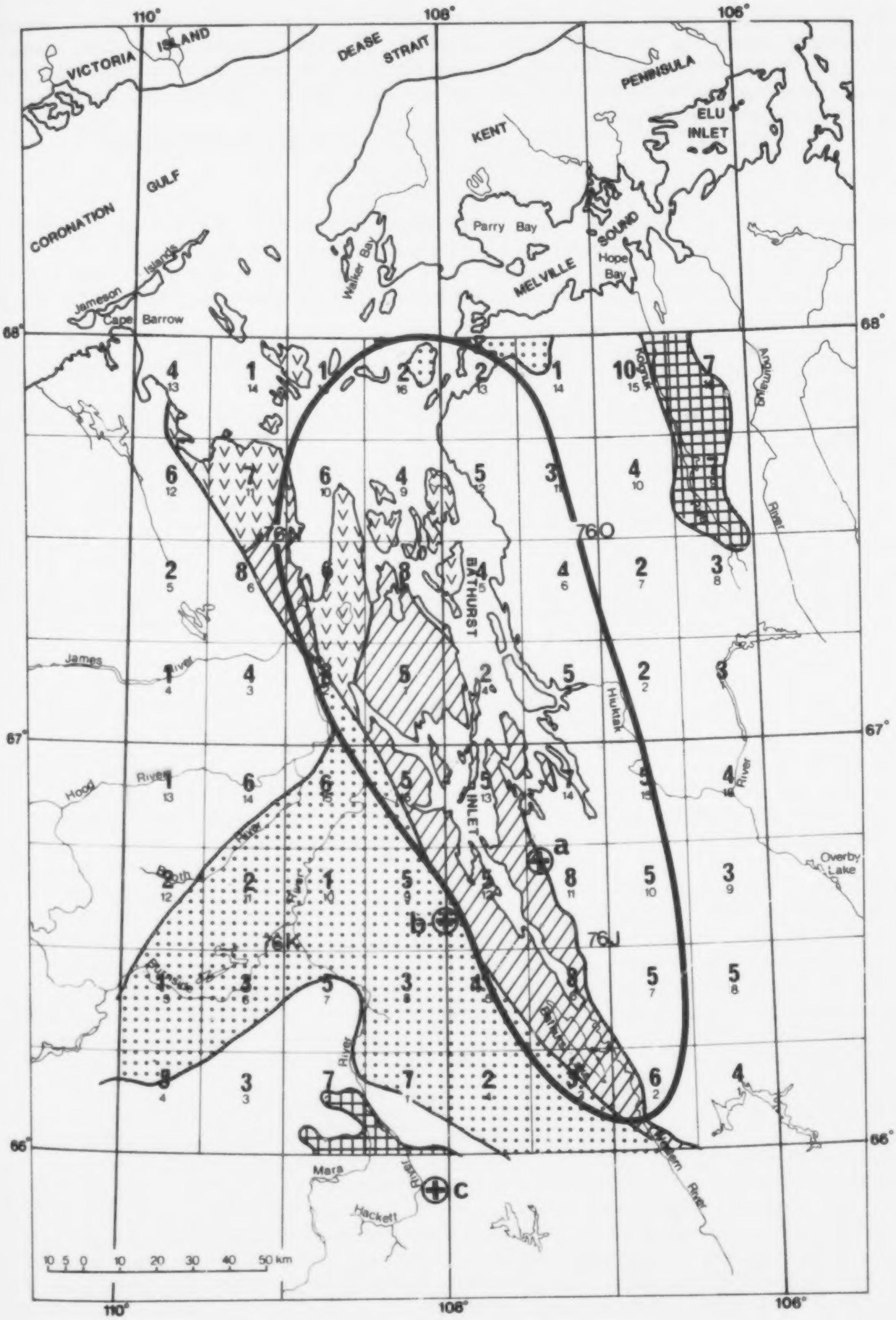

D
Copper (Zn,Pb,U)
C
Uranium (Cu,Pb,Zn,phosphate)
B
Uranium (Ag,Au,Ti,Ni,Cu)
A
Gold (base metals and silver in small unmapped areas of metavolcanics Li,Ta,Be,Sn, in pegmatites U near coast side of inlet)
A 1
Base metals and silver, gold
Mineral localities of special interest.(a)gold in iron formatio (b)uranium and gold in float (c)Bathurst Norsemines base metal deposits.
5
Discovery possibilities in NTS blocks are rated on a scale of 1 to 10.

FIGURE 3.—Commodities of principal interest in major metallic subdivisions. Commodities of secondary or speculative interest are shown in parentheses.



110°
108°
106°
VICTORIA ISLAND
DEASE STRAIT
KENT PENINSULA
ELU INLET
CORONATION GULF
Parry Bay
MELVILLE SOUND
Hope Bay
Walker Bay
Jameson Islands
Cape Barrow
68°
67°
66°
BATHURST INLET
76N
76O
76J
76K
James River
Hood River
Hiuktak
River
Overby Lake
Mara
Hackett
River
Western River
a
b
c
10 5 0 10 20 30 40 50 km

Archean volcanic rocks will certainly be explored again for base metal deposits particularly likely to be exploitable because of their proximity to the seacoast. Sometime in the future, if mining rights are available in the inlet area, potentially rich unconformity-related uranium deposits and perhaps copper deposits will be considered attractive exploration targets.

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CANADIAN EXPERIENCE IN APPLICATION OF MULTIVARIATE ANALYSIS TECHNIQUES

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ABSTRACT

Since 1967, multivariate statistical techniques have been applied in Canadian regional resource assessment studies to estimate the probabilities of occurrence of undiscovered metallic mineral deposits and to attempt to predict the sizes of these deposits. These applications are summarized in this paper. The techniques included multiple regression, discriminant analysis, and logistic regression. Precambrian rocks of the Canadian Shield (for example, the Abitibi volcanic belt) as well as Phanerozoic terrains in the Appalachian region and the Cordillerans have been analyzed by means of geologic map data and, to a lesser extent, geophysical and geochemical data. Sea-floor polymetallic sulfide deposits, gold-bearing quartz veins, and magmatic nickel-copper sulfides were among the types of ore deposits studied. Systems of computer programs have been developed for quantification, integration, and image analysis of map data and for multivariate statistical analysis of data quantified for cells. Suggestions for further research are given at the end of the paper.

INTRODUCTION

The expression "multivariate analysis" is used to denote the analysis of data that are multivariate in the sense that each observation bears the values of many variates (Kendall and Buckland, 1967, p. 195). The principal techniques of multivariate analysis are (multiple) regression, discriminant analysis, and factor analysis (Kendall, 1975). Regression analysis is often considered to be a subject in its own right (Draper and Smith, 1966; Vinod and Ullah, 1981).

The Canadian experience with using multivariate analysis to estimate parameters of mineral resource potential by geologic analogy began in 1967. Although it can be argued (Agterberg, 1981a) that the construction of a comprehensive regional data base and its usage for a computerized statistical resource appraisal may be an elusive task, research on this topic is fruitful, because it helps to establish basic concepts such as the probability of occurrence of mineral deposits of different types and its combination with frequency distributions of ore tonnages and metal grades. Moreover, because computer technology is moving at such a rapid pace, large regional data bases containing patterns for many types of geoscience data may become widely available in the future. Automated methods of relating these patterns to one another through metallogenic concepts (deposit models) should be further developed.

Figure 1 illustrates the three types of input required for performing a regional mineral resource appraisal by multivariate statistical methods. Dependent variables expressing the characteristic features of the mineral deposits in a region are to be correlated with independent variables that have been systematically quantified for the geologic framework. In general, the finding of orebodies requires major expenditures for local exploration consisting of detailed surveying and drilling. Areas that are well explored can be selected as control (or training) areas for extrapolation toward relatively

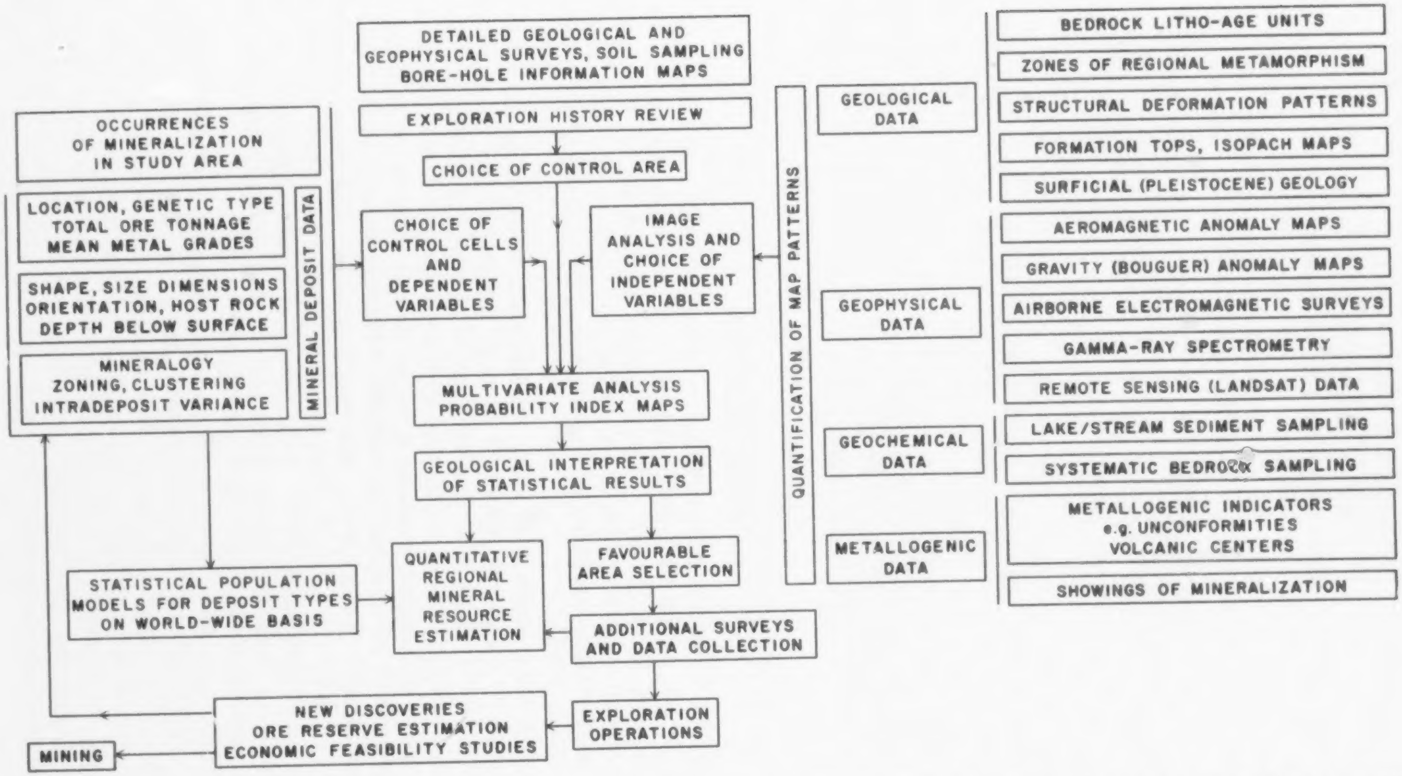

DETAILED GEOLOGICAL AND GEOPHYSICAL SURVEYS, SOIL SAMPLING BORE-HOLE INFORMATION MAPS
EXPLORATION HISTORY REVIEW
CHOICE OF CONTROL AREA
OCCURRENCES OF MINERALIZATION IN STUDY AREA
LOCATION, GENETIC TYPE TOTAL ORE TONNAGE MEAN METAL GRADES
SHAPE, SIZE DIMENSIONS ORIENTATION, HOST ROCK DEPTH BELOW SURFACE
MINERALOGY ZONING, CLUSTERING INTRADEPOSIT VARIANCE
MINERAL DEPOSIT DATA
CHOICE OF CONTROL CELLS AND DEPENDENT VARIABLES
IMAGE ANALYSIS AND CHOICE OF INDEPENDENT VARIABLES
MULTIVARIATE ANALYSIS PROBABILITY INDEX MAPS
GEOLOGICAL INTERPRETATION OF STATISTICAL RESULTS
QUANTITATIVE REGIONAL MINERAL RESOURCE ESTIMATION
FAVOURABLE AREA SELECTION
STATISTICAL POPULATION MODELS FOR DEPOSIT TYPES ON WORLD-WIDE BASIS
ADDITIONAL SURVEYS AND DATA COLLECTION
EXPLORATION OPERATIONS
NEW DISCOVERIES ORE RESERVE ESTIMATION ECONOMIC FEASIBILITY STUDIES
MINING
QUANTIFICATION OF MAP PATTERNS
GEOLOGICAL DATA
GEOPHYSICAL DATA
GEOCHEMICAL DATA
METALLOGENIC DATA
BEDROCK LITHO-AGE UNITS
ZONES OF REGIONAL METAMORPHISM
STRUCTURAL DEFORMATION PATTERNS
FORMATION TOPS, ISOPACH MAPS
SURFICIAL (PLEISTOCENE) GEOLOGY
AEROMAGNETIC ANOMALY MAPS
GRAVITY (BOUGUER) ANOMALY MAPS
AIRBORNE ELECTROMAGNETIC SURVEYS
GAMMA-RAY SPECTROMETRY
REMOTE SENSING (LANDSAT) DATA
LAKE/STREAM SEDIMENT SAMPLING
SYSTEMATIC BEDROCK SAMPLING
METALLOGENIC INDICATORS e.g. UNCONFORMITIES VOLCANIC CENTERS
SHOWINGS OF MINERALIZATION

FIGURE 1.—Schematic representation of the three types of input required for multivariate analysis in resource appraisal (Agterberg, 1981a).

less explored target (or study) areas. The independent variables are based on data for the geologic framework that have been gathered systematically according to the same methods in both control and target areas. A basic assumption is that the geologic environments of the mineral deposits (which may contain orebodies) are similar in control and target areas (geologic analogy). In practical applications, it is generally better to use multivariate models in which the control is assumed to be randomly distributed within the study area (Agterberg, 1971).

Multivariate mineral resource appraisal work in Canada can be summarized as follows:

1. Multiple regression of total dollar value on cell data (1967-71).
2. Two-stage least-squares model (1967-71).
3. Probability index maps and occurrence model for undiscovered deposits (1970-79).
4. Logistic model for estimating probability of occurrence (1971-80).
5. Quantification and analysis of geologic patterns (1971-80).
6. Automated coding and development of integrated computer systems for resource evaluation (1978-present).

In addition to multivariate analysis, other statistical methods have been developed and used for resource appraisal (see Garrett, this volume). Multivariate techniques are also used for other types of geologic data analysis (see Bonham-Carter and others, this volume).

MULTIPLE REGRESSION TO ESTIMATE TOTAL DOLLAR VALUE OF CELLS

In October 1967, A. M. Kelly and W. J. Sheriff of the British Columbia Research Council began a project entitled "A Statistical Examination of the Metallic Mineral Resources of British Columbia." They superimposed a network of cells on a 1:1,267,200-scale geologic map (Geological Survey of Canada, 1962). The relative areas of the lithostratigraphic units and other parameters such as lenghts of contacts of intrusive rock bodies were obtained for 818 cells measuring approximately 20 mi (32 km) on a side. In total, there were 75 geologic variables. The published metal production and reserve figures for about 1,500 orebodies were collected and converted into dollar values for the cells in which they occurred by using average 1967 metal prices. An area of 145 cells in southern British Columbia was taken as the control area for extrapolation by multiple regression to the larger target area of 673 cells in the remainder of the province. In their choice of cell size and definition of variables, Kelly and Sheriff followed Harris (1965). As a regression technique, they used backward elimination (Draper and Smith, 1966). Cell dollar value as the dependent variable was regressed on groups of independent variables consisting of combinations of the geological variables (Kelly and Sheriff, 1969; Agterberg, 1974a).

Two other multivariate studies using dollar values for cells were carried out at approximately the same time. Sinclair and Woodsworth (1970) used a grid having cell dimensions of 4 mi by 4 mi (6.4 km by 6.4 km) in the Terrace area of British Columbia, which had 50 known mineral deposits. The control areas consisted of individual cells situated within the 128-cell study area. They also used multiple regression (backward elimination) to obtain relations between the total dollar value of a cell and 12 geologic variables. In addition to dollar value, ore tonnage was used as a dependent variable. Sinclair and Woodsworth concluded that the method appeared to offer much practical potential, but they pointed out that subjective analysis of the results is a necessary requirement. Unrealistically high dollar values were predicted in some cells, and minor transformations of variables could change the results significantly.

DeGeoffroy and Wignall (1971) applied multiple regression and Bayesian classification analysis to 10 mi by 10 mi cells for an area of 17,000 mi^2 in the Grenville

Province of the Canadian Shield. As a result of this application, 11 cells having a total predicted ore value of $425 million were recommended for further exploration.

TWO-STAGE LEAST-SQUARES MODEL

A Geological Survey of Canada (GSC) pilot project to study the occurrence of vein-type gold deposits in western Quebec began in 1967. A regular grid having an 8-mi spacing was superimposed on geologic maps at a scale of approximately 1:250,000 (1 in=4 mi), and relative amounts per cell were coded for six rock types (granites and gneisses, mafic intrusive rocks, ultramafic rocks, early Precambrian sedimentary rocks, felsic volcanic rocks, and mafic volcanic rocks). The dependent variable consisted of number of gold occurrences per cell. The method of all possible regressions (Draper and Smith, 1966) was used indicating that the approximately 400 gold occurrences in this area are relatively strongly correlated with felsic volcanic rocks (rhyolites and pyroclastic rocks) and sedimentary rocks (especially those containing banded iron-formations). However, the gold-bearing quartz veins occur in distinct belts that cut across different rock types. A rock type that occurs within a belt has higher probability of containing gold deposits than that same rock type does when it occurs outside the belt. A related problem is that regression coefficients become biased when important independent variables are omitted. To cope with these difficulties, a two-stage regression model was developed. This method is equivalent to fitting polynomial trend surfaces of the same order to all variables considered; this initial step is followed by regression of residuals for the dependent varialbe (gold occurrences) on residuals for the independent variables (rock types). In this way, the belt structure was captured by means of the polynomial equations, and bias in rock type coefficients was reduced considerably (Agterberg and Cabilio, 1969; Agterberg, 1970; Agterberg, 1974a).

PROBABILITY INDEX MAPS AND CONTOURS FOR EXPECTED NUMBERS OF UNDISCOVERED DEPOSITS

Agterberg and others (1972) applied stepwise regression (Draper and Smith, 1966) to quantified geologic and geophysical data for equal-area cells to evaluate the Abitibi area in the Canadian Shield for its copper and zinc potential and to identify broad regional targets for exploration. Their report dealt with the massive and disseminated sulfide deposits in the Archean rocks of this region. The copper potential map resulting from this study is reproduced in figure 2. Only 41 deposits, each containing more than 1,000 tons (907.2 t) of copper, were considered. Later, Agterberg and David (1979) performed a hindsight study on this region. Seven new discoveries, each containing more than 1,000 tons of copper, are also shown in figure 2. These new deposits were found in areas of high copper potential, as predicted (fig. 3).

Three of the seven new deposits shown had actually been discovered by 1971 when the contour map was constructed, although published figures for production and estimated reserves were not available for them. The following remarks serve to explain briefly how the prognostic contours of figure 2 were determined and how they should be interpreted.

The multivariate method used for the contours in figure 2 is a version of a qualitative response model that assumes that, locally, mineral deposits or small clusters of deposits are distributed according to a simple Poisson process. The purpose of a statistical model of this type is to estimate the probability of occurrence of a discrete yes-no event on the basis of known data for a number of variables. The linear model of multiple regression can be used for estimating probabilities, although, in some applications, a nonlinear model (for example, a logistic model) (fig. 4) is to be preferred. The probability of one or more deposits per 10 km by 10 km cell was modeled

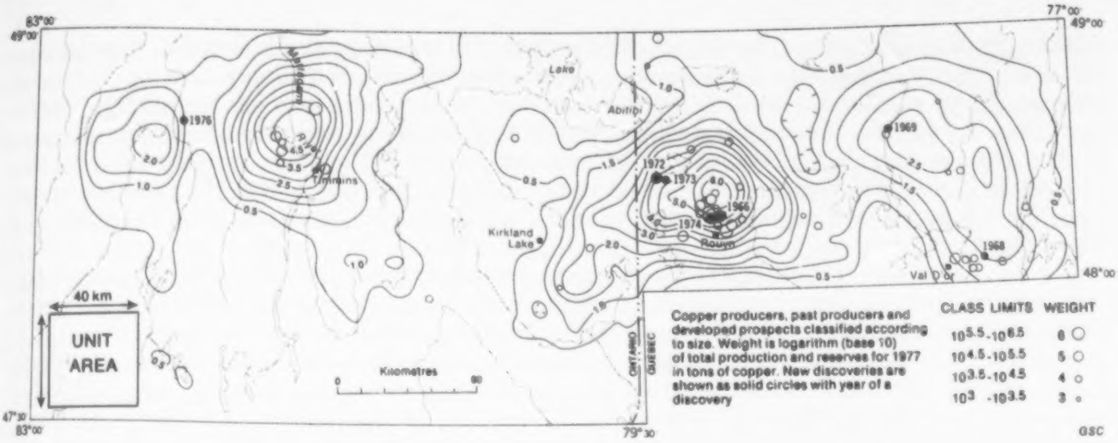

83°00'
49°00'
77°00'
49°00'
48°00'
47°30'
83°00'
79°30'
1976
Timmins
Lake
Abitibi
Kirkland Lake
1972
1973
1966
1974
Rouyn
1969
1968
Val d'Or
40 km
UNIT AREA
Kilometres
0
80
ONTARIO
QUEBEC
Copper producers, past producers and developed prospects classified according to size. Weight is logarithm (base 10) of total production and reserves for 1977 in tons of copper. New discoveries are shown as solid circles with year of a discovery
CLASS LIMITS
WEIGHT
$10^{5.5}$-$10^{6.5}$ 6
$10^{4.5}$-$10^{5.5}$ 5
$10^{3.5}$-$10^{4.5}$ 4
10^{3}-$10^{3.5}$ 3
GSC

FIGURE 2.—Copper potential map of the Abitibi area of the Canadian Shield. Prognostic contours were based on deposits shown as open circles (Agterberg and others, 1972). Contour value represents the expected number of events per 40 km by 40 km unit area. The event was defined as one or more deposits per 10 km by 10 km cell. The original coding was performed for 10 km by 10 km cells belonging to the Universal Transverse Mercator Projection grid (Agterberg and David, 1979).

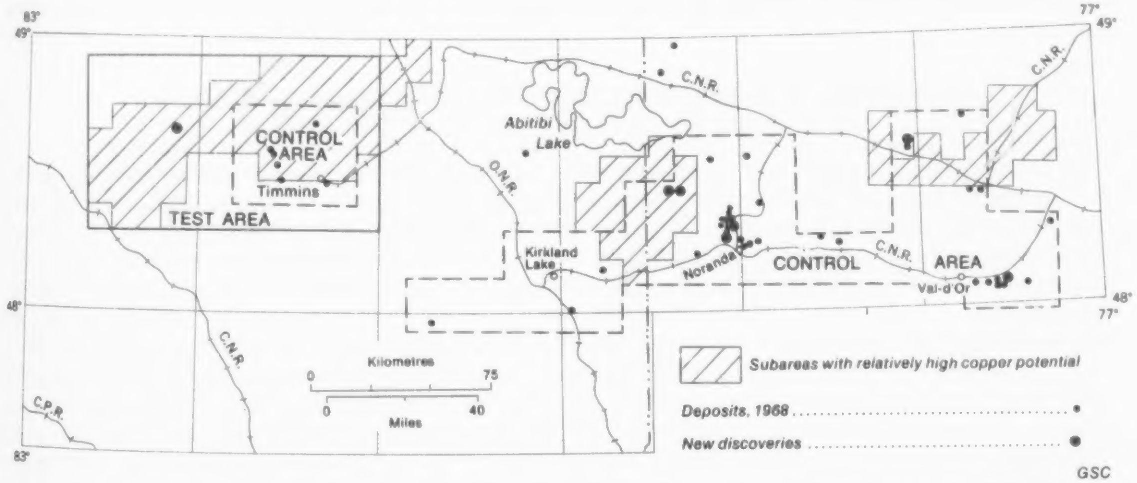

83°
49°
77°
49°
48°
48°
77°
83°
CONTROL AREA
Timmins
TEST AREA
Abitibi
Lake
C.N.R.
O.N.R.
Kirkland Lake
Noranda
CONTROL
AREA
Val-d'Or
C.N.R.
C.P.R.
Kilometres
0
75
0
40
Miles
Subareas with relatively high copper potential
Deposits, 1968
New discoveries
GSC

FIGURE 3.—Outlines of regional anomalies, control area, and test area in the Abitibi area of the Canadian Shield shown in figure 2. From Agterberg and others (1972).

as a linear function of 55 independent variables, each of which was a simple function of 10 lithologic and geophysical parameters coded for 10 km by 10 km cells belonging to the Universal Transverse Mercator grid shown on Canadian topographic maps at scales of 1:250,000 and larger. The 42 large copper deposits (fig. 2, open circles) occur in 27 of these 10 km by 10 km cells. Hence, there were only 27 observed yesses for the yes-no event. A standard computer program for stepwise regression was used for the calculations. The input for the dependent variables consisted of the logarithmically (base 10) transformed copper tonnage per cell or a zero value for cells without known deposits. The output for each 10 km by 10 km cell consisted of an estimated value which was transformed into a probability by the following method. A relatively well explored control area was defined in which the copper potential in undiscovered deposts was arbitrarily set at zero. As figure 3 shows, this control area contained most of the known deposits. The sum of the calculated values in the control area was multiplied by a factor such that it became equal to the number of cells containing one or more known deposits in the control area. Multiplication of the estimated cell values by the same factor yielded cell probabilities that were added for larger square-unit areas measuring 40 km on a side to obtain the expected values for the number of events per 40 km by 40 km cell (shown by contours in fig. 2).

The contour value in figure 2 represents the expected value of a probability distribution for the number of events per surrounding 40 km by 40 km cell. This probability distribution is approximately binomial. If, for example, the contour value m is equal to 3, then, on the average, the surrounding 40 km by 40 km cell will contain three events, an event being a 10 km by 10 km cell containing one or more deposits. However, the actual number of events, which can be written as k, is the realization of a random variable K having an expected value of 3. Application of the standard formula for the probabilities $P(K=k)$ of a binomial random variable gives 0.248 for the example $P(K=3)$. Although the average value is equal to 3, the probability that there are actually three smaller 10 km by 10 km cells containing one or more deposits per 40 km by 40 km cell when $m=3$ is only 25 percent.

The validity of the preceding results hinges mainly on the validity of two assumptions: (1) geologic analogy (the assumption that similar environments contain similar types of mineral deposits) and (2) the feasiblity of defining a relatively well explored control area in which the mineral potential consisting of undiscovered deposits is known.

COMMENTS ON PREDICTION OF TOTAL DOLLAR VALUES OR METAL TONNAGES IN SMALL REGIONS

In the preceding sections, either total dollar value was the dependent variable, or else frequency of occurrence for essentially one type of deposit was used. If the ore tonnage and metal grades of a deposit are statistically independent of its place of occurrence, these parameters can be combined with estimated probabilities of occurrence in a region by forming generalized random variables or by Monte Carlo simulation. If necessary, data for different types of deposits can be combined and a dollar value attached to the commodities. The two approaches then yield similar results.

The correlation between probability of occurrence and total amount of metal per cell was found to be very weak in some studies (Agterberg and others, 1972; Agterberg, 1973). This weakness would justify a "deposit model" type of approach in which the number of deposits of a given type in a region is estimated separately from the sizes and grades of the deposits belonging to a specific genetic type.

The values of m in figure 2 were scaled in such a manner that the expected number of cells with deposits (E_c) became exactly equal to the observed number of cells with deposits ($O_c=24$) in the relatively well explored control areas of 145 cells shown in figure 3. Hence, $E_c=O_c=24$.

Agterberg and others (1972) have shown that it is possible to estimate the expected number of cells containing deposits in a subarea of any size or shape by averaging the contours in figure 2 for that subarea. For example, the test area shown in figure 3 has an expected number of deposit cells $E_t=9.25$. There were $O_t=4$ observed cells containing one or more deposits in the area. The number of cells containing undiscovered deposits would, therefore, be $E_t-O_t=5$. It remains possible to use the contours in figure 2 when other assumptions are made on the relation between E_c and $O_c=24$. If, for example, $E_c=2O_c=48$, it follows that $E_t=19$ and $U_t=15$ for the test area.

The assumption $U_c=E_c-O_c=0$ implies that test areas containing undiscovered deposits where $U_t>0$ must fall mainly outside of the control area. Most of this copper potential was predicted to occur in the three large regional anomalies shown in figure 3. Although only seven new discoverces have been reported, the prediction in figure 2 is fulfilled in that these additional deposits occur either in the immediate vicinities of known deposits or on the broad regional anomalies shown in figure 3.

The average amount of copper per deposit cell was 140,000 tons (1 short ton multiplied by 0.907184 is equivalent to 1 metric ton.) Multiplying this value by $U_t=5$ gives 700,000 tons of copper potential. Agterberg and others (1972) determined the uncertainty of this estimate by Monte Carlo simulation. Combining an assumed positive binomial distribution for the occurrence of undiscovered deposits in the test area with random sampling of the empirical copper tonnage frequency distribution for the 27 deposit cells showed that the median was 400,000 tons of copper. The quartiles fell at 100,000 st and 1,150,000 tons. In other words, almost any amount of undiscovered copper could be present in this test area. At the time of the hindsight study (1978), a single new deposit of 24,000 tons had been discovered within the test area. The published reserves of the Kidd Creek mine (also within the test area) had increased by 2,298,000 tons during the preceding 10-year period. It is noted that the range of the average copper grades of the deposits used was relatively narrow in comparison with the very wide range of their ore and copper tonnage distributions.

The results of this case history study can be summarized as follows. It is suggested that predicted values for certain types of parameters (ore tonnages, metal tonnages, dollar values) are not meaningful statistics if they are estimated for small regions because of the great uncertainty associated with these numbers. On the other hand, several other parameters (place of occurrence of undiscovered deposits and metal grades) can be predicted with some confidence.

LOGISTIC MODEL FOR ESTIMATING PROBABILITY OF OCCURRENCE

Univariate qualitative response models for the prediction of discrete events have a long history in biometrics, where they are used to model, for example, the probability that an insect will survive a specific dose of poison. Walker and Duncan (1967) have developed a multivariate logistic method in which the probability of an event is expressed as a function of several variables. If the probability of an event is considered, the outcomes predicted by the model are qualitative. Hence, these models are known as qualitative response models.

Agterberg and others (1972) and Agterberg and Robinson (1972) used a modification of multiple regression as a qualitative response model to estimate the probability that mineralization will occur in a cell for which many parameters are know. In a discussion of this method, Tukey (1972) suggested that the logistic model might be applicable in this situation. Agterberg (1974b) applied Walker and Duncan's (1967) method as follows. The probability P that one or more deposits occur per cell (for example, per 10 km by 10 km cell) can be written as

$$P=[1+\exp(-\sum_{i=0}^{p} a_i x_i)]^{-1}$$

where the $a_i (i=0, 1,\ldots,p)$ are coefficients, $x_0=1$, and the $x_i (i=1,\ldots,p)$ represent the p variables quantified for each cell. One advantage of this type of transformation is that P becomes truly a probability when $0 \leq P \leq 1$. P is the expected value of a random variable Y, Y, which has only two possible realizations (y=0 and y=1). In Agterberg's (1974b) example, the coefficients a_i and probabilities were estimated for a set of lithologic variables to describe the occurrence of two types of sulfide deposits (polymetallic massive and nickel-copper) in a part of the Superior Province of the Canadian Shield. The results for both types are shown in figure 4, where the contours represent the sum of 16 probabilities contained in 40 km by 40 km cells. As it did in figure 2, this sum denotes the expected number of events per unit area. Agterberg (1974b) and Chung (1978) have presented more detailed descriptions of the method.

The probabilities represented in figure 4 have been compared with those estimated by means of the linear model

$$P = \sum_{i=0}^{p} b_i x_i$$

having coefficients b_i $(i=0, 1,\ldots,p)$ that can be obtained by a computer program for multiple regression. The logistic model and the linear model gave similar results for the polymetallic massive sulfide deposits, but a satisfactory solution for the nickel-copper sulfide deposits could not be obtained by the linear model, the suggestion being that the multivariate logistic model can be useful if a region contains relatively few deposits of the type considered. The logistic model is a nonlinear model, and several iterations may be required to solve for the coefficients a_i $(i=0, 1,\ldots,p)$. A computer program for this technique has been published by Chung (1978).

Simard (1980) has used the logistic model to estimate the probability that a nickel sulfide deposit occurs at a drill site for which various geophysical variables (such as gravity and aeromagnetic data) are available.

The qualitative response model has definite advantages with respect to other multivariate statistical methods applied to cell data if mineral deposits are regarded as discrete events. In classical regression techniques, the dependent variable is continuous, a feature that may not be desirable for prediction of yes-no type data. Likewise, the drawback in discriminant analysis is that cells in an area are allocated to two or more distinct populations, whereas, in reality, the probability of occurrence of mineral deposits in a cell is probably a continuous function whose value depends on the values assumed by the variables for that cell. These difficulties are avoided when a qualitative response model is used.

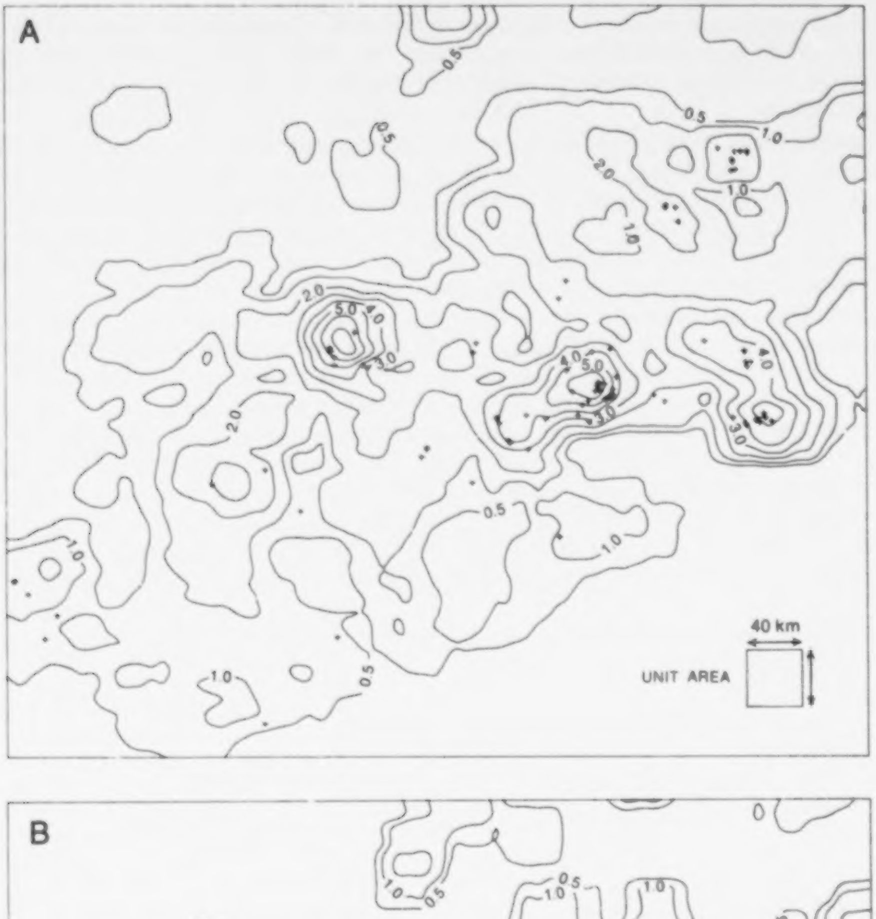
The logistic model does not need a count of the number of mineral deposits per cell as an input requirement. This feature can be desirable if mineral deposits exhibit local clustering. When mineral deposits can be regarded as points, Poisson regression (Chung and Agterberg, 1980) is a theoretically appropriate model for relating them to their geologic environment.

QUANTIFICATION AND ANALYSIS OF GEOSCIENCE PATTERNS

The preceding multivariate studies made use of geologic and geophysical data quantified for square cells. During the 1970's, several studies were made in which the emphasis was on improving the choice of the variables before a multivariate analysis was performed. This work began with the construction of a large data bank containing information on about 8,500 10 km by 10 km cells (Fabbri, 1975). Differences between map legends led to consultations with geologists familiar with the different regions. A data integration study in the Canadian Appalachian region, Project Appalachia (Leech, 1975), used concepts on regional geology, mineral deposits and multivariate statistical

FIGURE 4.—Contour maps for expected number per 40 km by 40 km cell of 10 km by 10 km cells that contain one or more deposits (after Agterberg, 1974b). The multivariate logistic response model was applied to 36 lithologic variables defined for 10 km by 10 km cells in the Abitibi volcanic belt of the Canadian Shield. A, Volcanogenic massive sulfide deposits. B, Nickel-copper sulfide deposits. Known deposits are shown as crosses. The dependent variables were 1 for the presence of deposits and 0 for the absence of deposits in 10 km by 10 km cells. In total, figure 4A used 87 deposit cells consisting of 59 deposit cells from within the area shown and 28 cells from elsewhere in the Superior Province of the Canadian Shield. Figure 4B used 25 deposits cells for control, 16 being inside the area shown and 9 being outside.

▶


A
0.5
1.0
2.0
3.0
4.0
5.0
40 km
UNIT AREA
B
0.5
1.0
2.0
3.0
4.0
40 km
UNIT AREA

techniques for regional mineral resource appraisal. Regional and economic geologists participated with mathematical geologists in this study, which concluded that experiments in computer modeling stimulated better definition of conceptual models of geologic processes.

A geophysical data integration study having multivariate statistical applications was performed by Assad and Favini (1980) in northwestern Quebec. The emphasis in this project was on defining gravimetric and aeromagnetic anomalies precisely and combining them with local topographic and geologic data to delineate drilling sites favourable for the occurrence of massive sulfide deposits. Favini and Assad (1979) used discriminant analysis to distinguish between sites with orebodies and sites without.

Automated methods for coding map data (Fabbri, 1980) and multivariate statistical analysis of cell data (Chung, 1983) have been under development at the GSC since 1978. Figures 5 through 8 present one application of these methods by Agterberg and others (1981) in the southern district of Keewatin in the Northwest Territories. The automated coding is facilitated by image-processing techniques (figs. 6, 7). SIMSAG (System of Interactive Computer Programs for Multivariate Statistical Analysis of Geoscience Data), developed by Chung (1983), allows rapid choice of control areas, transformations of variables, type of statistical technique to be used, and applications to target areas by the user in front of a video terminal (fig. 8). Bonham-Carter and Chung (1983) have presented another example of application of SIMSAG with geochemical data.

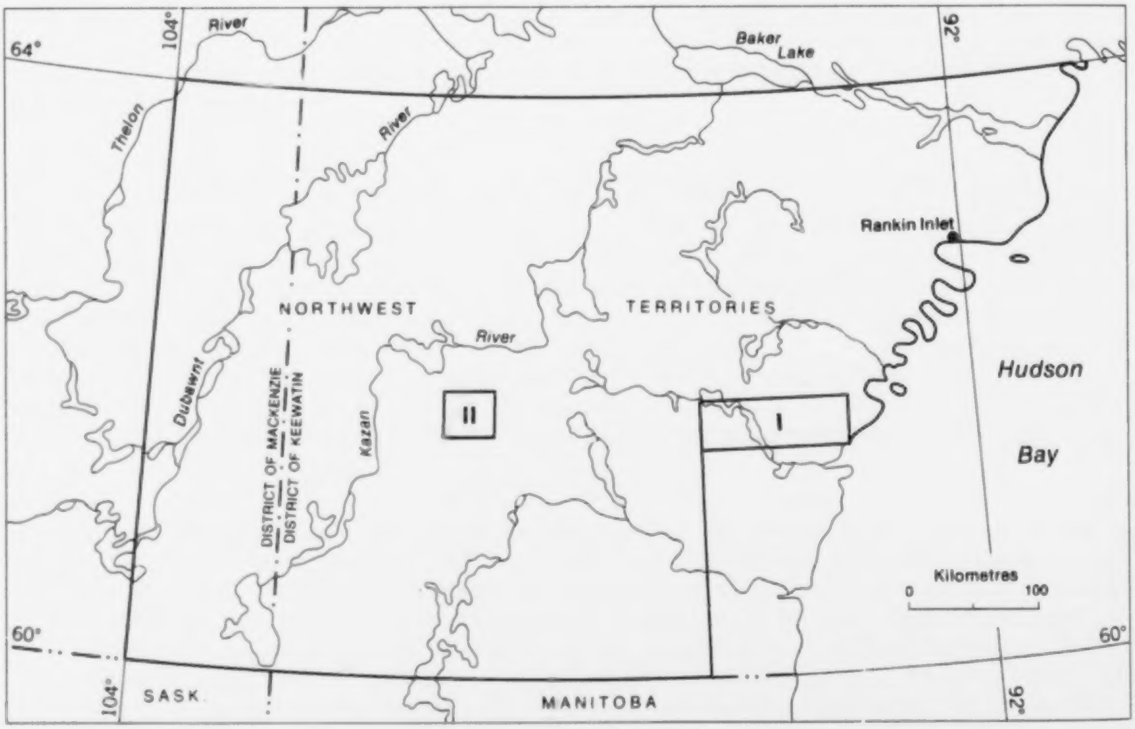


FIGURE 5.--Location map of the Keewatin district, Northwest Territories. Example of picture processing followed by automated multivariate analysis. Subareas I and II are used in figures 6 and 7, respectively (Agterberg, 1981b).

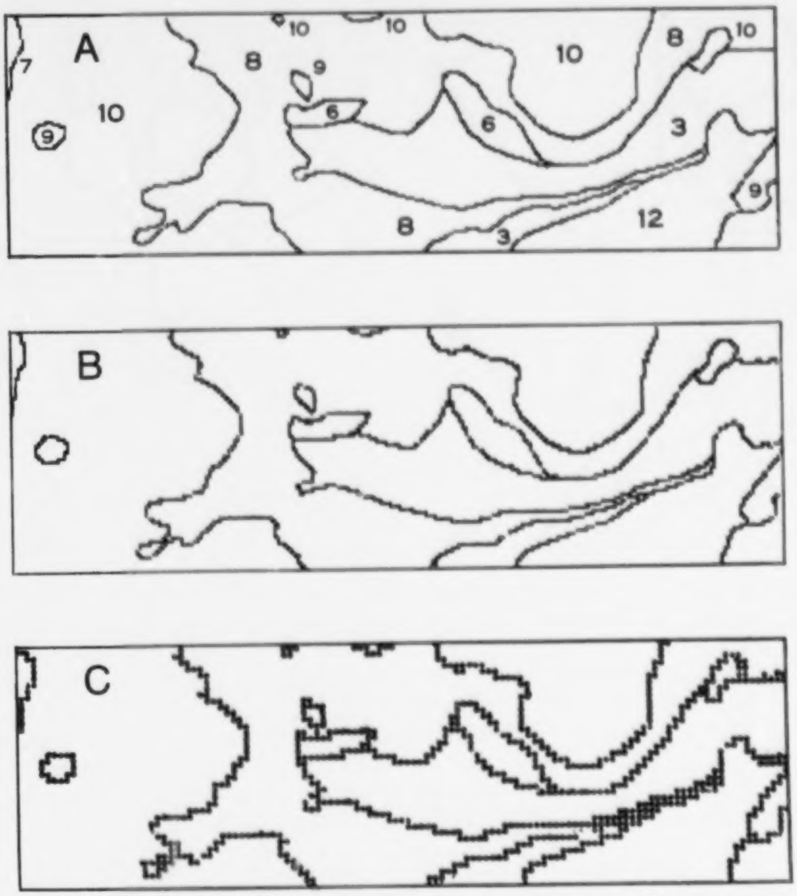


FIGURE 6.—Digital images for three different resolutions extracted from a set of contacts digitized in vector mode for subarea I (fig. 5). Each picture point (pp) represents a grid cell that was crossed by a contact. These plots were obtained on a dot matrix printer. Ages of rock types shown in figure 6A are Archean; 3 indicates graywacke and slate and minor tuff; 6, felsic to intermediate volcanic rocks; 7, undifferentiated volcanic rocks; 8, mafic volcanic rocks (includes minor intrusive rocks); 9, granodiorite, quartz monzonite, and syenite; 10, quartz diorite, diorite, and gabbro; 12, gneisses (quartzofeldspathic, migmatite, layered gneisses) (extracted from data base used by Agterberg and others (1981)). A, 1 pp=375 m; B, 1 pp=500 m; C, 1 pp=1,000 m.

SUGGESTIONS FOR FURTHER RESEARCH

Multivariate analysis techniques in mineral resource appraisal suffer from the fact that mineral deposits are rare events and have some parameters (size, grade, dollar value) whose occurrence can be predicted only with a very large uncertainty. Nevertheless, it is possible to determine the relative favorability for the occurrence of

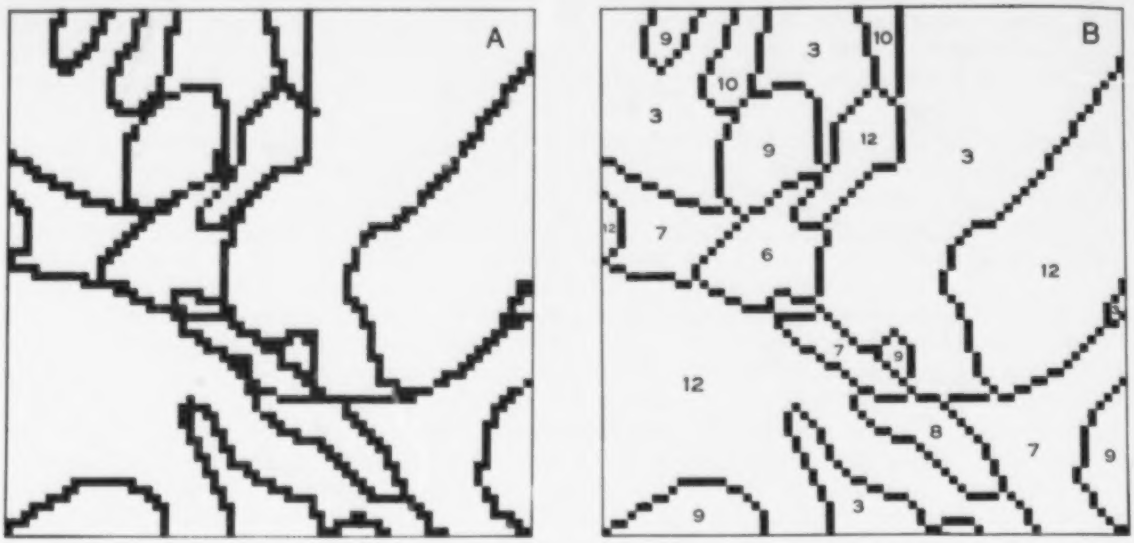


FIGURE 7.—Line-thinning technique applied to an edited digital image for 500-m resolution extracted from the set of contours digitized in the vector mode for subarea II (fig. 5). Pattern in figure 7A was changed into the pattern in figure 7B. Ages of rock types shown in figure 7A are Archean; 3 indicates graywacke and slate and minor tuff; 6, felsic to intermediate volcanic rocks; 7, undifferentiated volcanic rocks; 8, mafic volcanic rocks (includes minor intrusive rocks); 9, granodiorite, quartz monzonite, and syenite; 10, quartz diorite, diorite, and gabbro; 12, gneisses (quartzofeldspathic, migmatite, layered gneisses) (extracted from data base used by Agterberg and others (1981)).

certain type of deposits. One advantage of statistical methods is that they are objective and allow experiments to establish reproducibility. Drawbacks in comparison with subjective methods of resource appraisal are (1) that the information that can be systematically quantified generally constitutes only a small part of the worldwide pool of information relevant to the occurrence of mineral deposits in a region and (2) that statistically computed weighting factors may provide good estimates of probabilities of occurrence but generally cannot be readily interpreted or applied in other regions. The second drawback remains even if stepwise methods or ridge regression are used.

Further improvements of occurrence models can be achieved by developing better methods for considering the logical interactions of variables. The Abitibi copper potential study (fig. 2) found that significant improvements resulted from using logical product variables (such as the presence of acidic volcanic rocks and the Bouguer gravity anomaly above its regional average). The "deposit models" developed by mineral deposit geologists would provide basic input for such new models, but further research is needed to translate these concepts into mathematical terms.

New techniques of mathematical statistics are continually being developed. Methods to study the influence and leverage of individual observations on regression results have become available during the past 8 years. Agterberg and Franklin (in press) have applied some of these methods in a study on expressing the probability of occurrence of hydrothermal vents in terms of volcanic and tectonic variables on the ocean floor. In discussing a recent review paper by Agterberg (1984), Tukey (1984) made several suggestions for improving multivariate occurrence models, including using other transformations of variables and the definition of other types of cells with boundaries determined by geologic discontinuities. The three-dimensional aspect of map data has

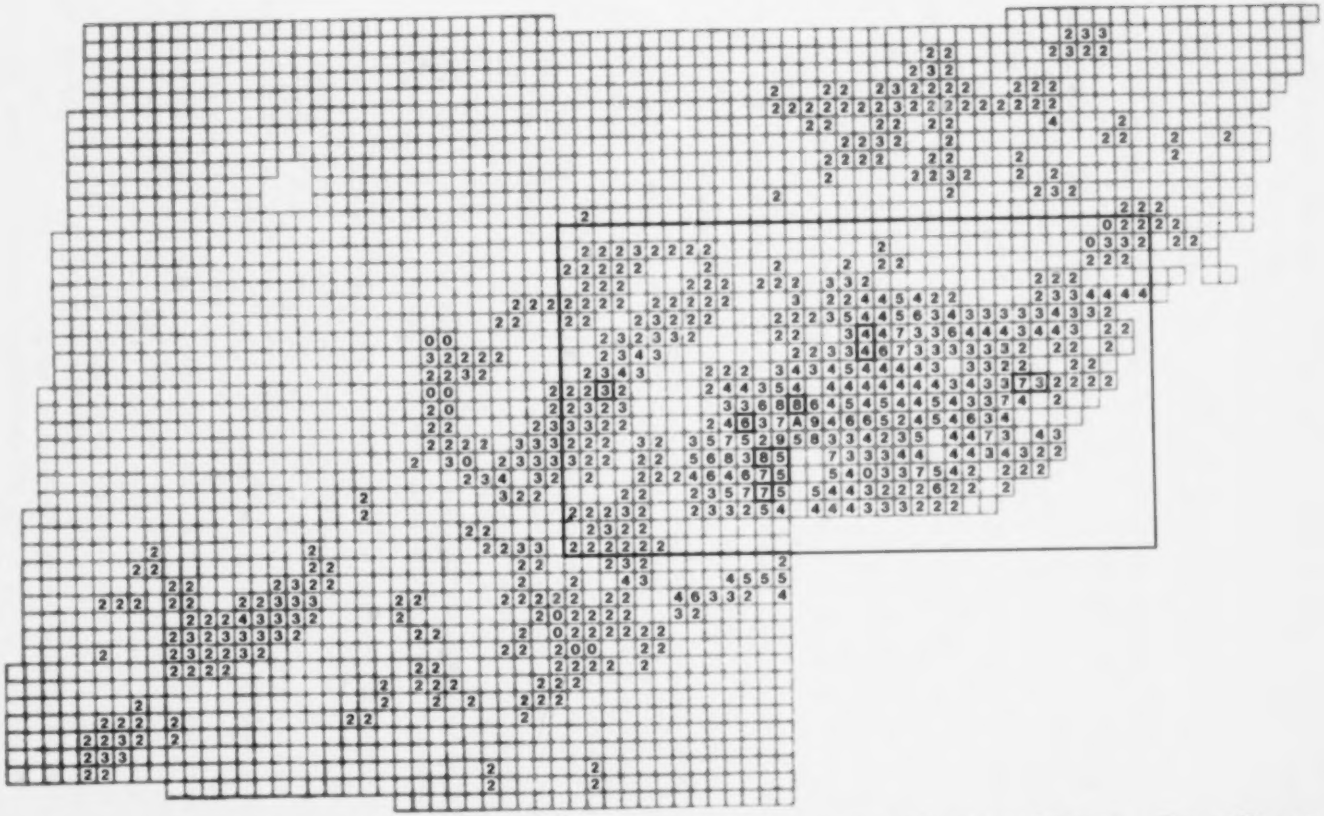


FIGURE 8.—Set of 10 km by 10 km cells used for the study area outlined in figure 5. The cells are rated for their relative favorability to contain undiscovered volcanogenic massive sulfide deposits on a linear scale ranging from 0 to 9. The rectangular control area and cells containing known deposits are bounded by heavy lines. A (0.2538) indicates the largest value in the control area obtained by stepwise regression on variables for the presence or absence of Archean rock types in obtained by stepwise regression on variables for the presence or absence of Archean rock types in 10 km by 10 km cells. Cell boundaries were photographed from a display originally obtained on graphic terminal using SIMSAG; numbers were entered manually from hard copy of the visual display.

hardly been considered at all in applications of multivariate analysis techniques. In addition, the continued development of integrated computer systems for data management, statistical analysis, and graphic display such as SIMSAG (Chung, 1983) would enhance the future advancement of quantitative methodology in mineral resource evaluation. The new multivariate models that remain to be further developed should be tested in practical applications.

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EXPLORATION GEOCHEMICAL RESEARCH IN REGIONAL RESOURCE ASSESSMENT IN THE U.S. GEOLOGICAL SURVEY

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The role of exploration geochemistry in the U.S. Geological Survey (USGS) in regional resource assessment is (1) to increase understanding of the geochemical evolution and structure of different mineral deposit types; (2) to identify the secondary geochemical processes that modify mineral deposits; (3) to develop chemical and geochemical tools to aid in the exploration for and evaluation of mineral deposits; and (4) to develop techniques for interpreting geochemical data.

The immediate objectives of exploration geochemistry in regional resource assessment programs are to provide data to determine the different types of mineralization, the regional distribution of metals, and the extent of mineralization. To these ends, research investigations are being conducted on a diversity of scientific problems. For example, to better understand primary geochemical dispersion and to set guidelines for exploration, several projects are studying the geochemistry and genesis of specific mineral deposit types, from epithermal precious-metal deposits to metamorphic base- and precious-metal deposits to volcogenic cobalt-copper deposits. Secondary processes are becoming better understood through studies in different climatological environments such as the tropical environs of the Caribbean Basin and the arid Southwestern United States. In addition, research related to partial dissolution techniques are aiding in the choice of proper sample media and extraction procedures for analytical work, enhancing geochemical contrasts to improve anomaly recognition, and assissting in the interpretation of regional data by identifying processes related to weathering

The interpretation of regional geochemical data is best accomplished within the context of the regional geologic framework and conceptual geologic process and ore deposit models. This paper illustrates applications of regional geochemical exploration data in resource assessment programs through three case studies.

PIONEER BATHOLITH, MONTANA: A CASE STUDY OF THE IMPLICATIONS OF ORE DEPOSIT GENESIS FOR MINERAL RESOURCE ASSESSMENT

By Byron R. Berger

Introduction

Detailed study of the chemistry and cooling history of the Cretaceous composite Pioneer batholith of Beaverhead County in southwestern Montana has facilitated an understanding of the geochemistry of batholith-related mineral deposits in the context of the evolution of the batholith, which is calc-alkaline in composition and was emplaced between 83 and 65 Ma (Snee, 1982). A variety of mineral deposit types are associated with various phases of the batholith, including tungsten- and copper-bearing skarns, copper-molybdenum and molybdenum porphyry-type deposits, and precious- and base-metal-bearing veins. Geochronological and geochemical studies of the plutons and of the major mining districts in the vicinity of the batholith show that a similar characteristic trace-element suite is found in the primary minerals of many plutons in the batholith, regardless of their whole-rock composition, and that mineral deposit types are related both to the chemical composition of plutons and to the cooling history of the batholith as a whole. The results of the geochemical studies on the Pioneer batholith and related mineral deposits will be a valuable guide to any mineral resource assessment in the region.

Geologic Setting

The Pioneer batholith makes up the core (approximately 285 mi^2) of the Pioneer Mountains, a north-south-trending range comprised of eastern and western sections. Plutonic rocks crop out from altitudes of about 6,000 to more than 11,000 ft. The western part of the range is a more rolling terrane than the rugged, alpine eastern section.

The batholith ranges in composition from hornblende gabbro to muscovite-biotite granite. Berger and others (1983) divided the batholith into groups of plutons that are similar in rock type, mineralogy, chemistry, and age (table 1). The relative ages of the plutons were determined by crosscutting field relationships. The groups show a general compositional trend from mafic to felsic through time. The cooling history of the batholith was determined by Snee (1982) by means of conventional K-Ar and ^{40}Ar/^{39}Ar mineral-dating techniques.

Sedimentary and metamorphic rocks varying in age from Precambrian to Cretaceous are intruded by the Pioneer batholith. The oldest Precambrian rocks are small exposures of gneisses and amphibolites that predate the deposition of the Middle Proterozoic Belt Supergroup. Belt rocks are widespread in the Pioneer Mountains, particularly in the western part of the range, and consist primarily of quartzite and argillite. Paleozoic miogeoclinal carbonates, sandstones, and shales are most commonly exposed in the eastern Pioneer Mountains. Triassic to Cretaceous sandstone, conglomerate, and shale crop out along the eastern flank of the range.

The Pioneer Mountains are located near the eastern edge of the Rocky Mountain fold and thrust belt. Thrust faults imbricate the prebatholithic Precambrian and Phanerozoic rocks. Broad, open folds are common in the Precambrian metasedimentary rocks, whereas the Phanerozoic rocks are completely folded. High-angle faults are numerous and are both preplutonic and postplutonic in age. Two high-angle fracture directions, west-northwest and north-northeast, control much of the structure of the Pioneer Mountains and the emplacement of the batholith (Snee, 1982). A north-trending fault system, locally known as the Comet-Fourth of July fault, separates the Pioneer Mountains into its two major eastern and western components.

Mineralization

A variety of metallic mineral deposit types are found in the Pioneer Mountains. These types include fissure veins, carbonate replacement deposits, and porphyry-type deposits. Many individual deposits were formed in conjunction with the emplacement of the Pioneer batholith, a comprehensive compilation of which is found in Geach (1972). The trace-element chemistry of the deposits was studied by Berger and others (1979a).

Open-space-filling quartz fissure veins along faults, fractures, and joints are the most common type of deposit within and around the Pioneer batholith. The veins vary in width from a few inches to several feet, and the wall rock is commonly altered to quartz, sericite, chlorite, and occassionally potassium feldspar. Primary ore minerals include tetrahedrite, native gold, galena, sphalerite, and chalcopyrite with associated pyrite and, commonly, arsenopyrite and huebnerite. Secondary minerals include cerargyrite, native

TABLE 1.—A summary of the primary and alteration minerals of the major plutons in the Pioneer batholith (from Berger and others, 1983)

			PRIMARY MINERALOGY													ALTERATION MINERALOGY					
	PLUTON	GROUP	Plagioclase (An_x)	Potassium Feldspar	Quartz	Biotite	Hornblende	Muscovite	Epidote	Magnetite	Sphene	Apatite	Zircon	Allanite	Pyroxene	Epidote	Chlorite	Sereite	Biotite	Potassium Feldspar	Quartz
OLDER	Diorite	I	50		●	●	●			●	●	●			●	★	★	★			
	Tonalite of Foolhen Mountain		70 35–	●	●	●	●		●	●	●	●	●	●	●	★	★		★		
	Tonalite of Pattengail Creek	IIa	70 20–	●	●	●	●		●	●	●	●	●	●	●	★	★		★		
	Pluton of Stine Creek		40 20–	●	●	●	●	▲	●	●	●	●	●	●		★	★	★			
	Granodiorite of Uphill Creek	IIb	50 20–	●	●	●	●		●	●	●	●	●	●			★				
	Granodiorite of Shoestring Creek		45 25–	●	●	●		▲	●	●	*	●	●	●			★				
	Granodiorite of Odell Lake	IIc	30	●	●	●		▲		●	*	●	●	●			★				
	Granodiorite of Francis Creek		30	●	●	●		▲		●	*	●	●	●			★				
	Granodiorite of Stone Creek		35	●	●	●		▲		●		●	●	●			★				
	Granodiorite of Doolittle Creek		25	●	●	●		▲		●	*	●	●	●			★				
	Rhyodacite porphyry	IIIa	20	●	●	●											★				
YOUNGER	Rhyolite porphyry	IIIb		●	●	●												★		★	★
	Granite of Salefsky Creek	IIIc	30 3–	●	●	●		●		■		●	●				★	★			
	Granite of Bryant Creek		20	●	●	●		●		●		●	●				★	★			

Key: ● = mineral present as primary phase
▲ = Late-stage phase, ragged
■ = magnetite and ilmenite
* = altered to leucoxene
★ = alteration mineral

metals, cerrusite, hemimorphite, malachite, and chrysocolla. Many mines are localized along major throughgoing fault systems, and some are localized in fractures related to antiformal structures. Throughout the region, most mineral production has come from secondary mineralization in the oxidized upper portions of the veins.

Two important types of carbonate replacement deposits occur in the region: tungsten-bearing garnet-pyroxene-epidote skarns and precious- and base-metal-bearing mantos and chimneys. The productive skarns occur at contacts with granodioritic phases of the Pioneer batholith. The skarns consist of andradite garnet, diopsidic pyroxene, epidote, quartz, and calcite. The main ore mineral is scheelite, but there may be associated molybdenite, chalcopyrite, sphalerite, and galena. Bismuthinite and beryl are found occasionally. Base- and precious-metal replacement deposits occur in Paleozoic dolomitic carbonate rocks near contacts with the Pioneer batholith. The selective replacement of bedding away from feeder structures creates mantos, and replacement along structures creates chimneys or veins of quartz and calcite with galena, sphalerite, chalcopyrite, tetrahedrite, and pyrite with occasional molybdenite.

The Pioneer Mountains contain a number of porphyry-molybdenum-type prospects and deposits. These large-tonnage deposits are associated with group IIIb granitic phases (table 1) of the Pioneer batholith and occur as stockworks of quartz veinlets. Alteration minerals include quartz, potassium feldspar, sericite, chlorite, pyrite, and magnetite. Intrusion breccias, intrusive breccias, and pebble dikes occur at some prospects. The multiple intrusion of leucocratic granite or rhyolite porphyry dikes is an important attribute of this type of deposit. The most significant ore mineral is molybdenite, and there may be associated chalcopyrite and fluorite. Galena and sphalerite occur rarely. Vein occurrences of silver and base metals with huebnerite are common around these deposits.

Geochemical Studies

Geochemical investigations in the batholith were started by Zen and others (1975) to determine the composite nature and age relationships within the batholith. Snee (1978, 1982) and Snee and Sutter (1978, 1979) extended this work. All of these studies found the batholithic rocks to be calc-alkaline and to compositionally overlap the sodic series of Tilling (1973) for the nearby Boulder batholith. Additionally, interpretations of geochemical data suggest that the plutons are comagmatic (Snee, 1982) and that the magma sources are in older crustal rocks (Zen and others, 1980).

Snee (1982) found that $^{40}Ar/^{39}Ar$ mineral dates from all of the pluton groups (table 1) reflect a westward decrease in the regional cooling rate (using the 280°C cooling isotherm) that is independent of pluton composition, emplacement, and distribution. Additionally, the pattern of dates shows that the cooling rate decreases toward the center of the batholith. The consequence of these two cooling trends is a northwestern zone of slow cooling rates interrupted only by the north-south Comet-Fourth of July fault zone. Snee (1982) interpreted this cooling trend to mean that the crustal levels at which the interior part of the batholith was emplaced were deeper than those at which the margin was emplaced and that the elongated northwest-trending slower cooling rate is due to a structural zone that ultimately brought the interior of the batholith to the same levels as the margins. The cooling data bracket the timing of uplift between approximately 72.5 and 70 Ma (Snee, 1982). The westward trend in cooling suggests a tilting of the uplift along the northwestern axis, away from the axis to the northeast and southwest.

Geochemical studies of the mineral deposits in the Pioneer Mountains were started by the USGS in 1978 (Berger and others, 1979a, b, 1980, 1983; Breit, 1980; Pearson and Berger, 1980; Chesley, 1986). The area contains potential resources for a variety of commodities including silver, gold, molybdenum, tungsten, lead, zinc, and copper. In addition, many of the deposits contain minor amounts of arsenic and antimony, trace amounts of bismuth and cadmium, and sporadic trace amounts of tin. The analyses of hornblendes and sphene from older granodiorites in the batholith show high concentrations of molybdenum, tungsten, and (or) tin; these results indicate that the batholith may be intrinsically enriched in these elements and that they are not wholly unique to any pluton composition, pluton age, or mineral deposit type.

$^{40}Ar/^{39}Ar$ alteration mineral dates from most of the mining districts around the Pioneer batholith show the deposits to be related genetically to the plutonism. The repeated spatial association of precious- and base-metal-bearing quartz veins with porphyry-type deposits suggests a genetic relationship. The work by Snee (1982) and unpublished age determinations (L. W. Snee, 1980) indicate that mineralization in and around the Pioneer batholith may be divided into three age-related stages: early-stage porphyry, vein, and skarn deposits, intermediate-stage porphyry and vein deposits, and late-stage porphyry and vein deposits.

Early-stage mineralization (pre-70 Ma) is related to the emplacement of dacite to granodiorite composition plutons. These porphyry-type deposits contain more copper than molybdenum, and the related vein deposits were mined extensively for silver, gold, lead, and zinc. The intermediate-stage mineralization (about 65-68 Ma) is related to the emplacement of granodiorite to biotite granite composition plutons. The granodiorite produced copper-bearing skarn and some tungsten skarn. The porphyry-type deposits of the intermediate-stage mineralization contain more molybdenum than copper and are related to the emplacement of biotite granite and "quartz-eye" rhyolite porphyry dikes. Quartz veins, which commonly contain huebernite, produced some precious and base metals. The late-stage mineralization (about 62 Ma) consists almost exclusively of molybdenum porphyry-type deposits associated with leucocratic granite dikes and "quartz-eye" rhyolite porphyry dikes. None of the vein deposits associated with the late-stage mineralization have been mined, and no metalliferous skarn deposits of this age are known.

Chesley (1986) studied the oxygen and hydrogen isotopes of intermediate-stage molybdenum porphyry and related fissure vein mineralization and found that only magmatic water, not meteoric water, was involved in the metallization. Additionally, his study of fluid inclusion data found that metal deposition took place at 350° to 450°C. When these data are used in conjunction with the cooling history of the Pioneer batholith, it appears that major hydrothermal cells involving either magmatic or meteoric water did not occur within the interior part of the batholith during early-stage plutonism.

Conclusion

Geochemical studies in the Pioneer batholith indicate that the composition of individual plutons and the cooling history of the batholith were important to the types of ore deposits formed at any given time and possibly also important to the economic productivity of porphyry-related vein-type deposits. As a result of studies in the Pioneer batholith, three stages of mineralization have been identified: (1) early (pre-70 Ma), (2) intermediate (65-68 Ma), and (3) late (62 Ma). Copper-molybdenum porphyry deposits appear to occur only in the early-stage mineralization, related to more mafic portions of the batholith. They are absent in the central, slower cooling region, although older granodiorites are present in this central region. The central portion of the batholith contains only deposits that are post-68 Ma in age (intermediate- and late-stage mineralization). At this time, the entire batholith had cooled to below 280°C, and there was additional intrusive activity. These intermediate- and late-stage deposits are molybdenum porphyries and related veins. In the more deeply emplaced and more slowly cooling parts of the batholith to the west and northwest, these molybdenum porphyry-type deposits become more pegmatitic, and intrusion breccias are more common.

This study on the genesis of mineral deposits in the Pioneer Mountains has identified several important implications for mineral resource assessments and exploration geochemistry in batholithic terranes.

1. Sampling programs involving heavy-mineral concentrate and stream-sediment surveys are likely to generate samples that contain metals from silicates, oxides, and sulfides. The heavy-mineral concentrate samples taken in the Pioneer Mountains consist of about 75 percent sphenes derived from the Pioneer batholith (B. R. Berger, unpublished data, 1979); these sphenes contain up to 30 ppm Mo, 30 ppm W, and 300 ppm Sn. Discriminating this metal source from sulfide sources requires special sample preparation or selective chemical leaching techniques.
2. All of the mineral deposit types, regardless of stage, contain a characteristic trace-element suite (Berger and others, 1979a). A discriminant function analysis of rock samples from all types of mineral deposits shows that porphyry-type, skarn, and vein-type deposits are distinguishable only through the use of uncharacteristic trace elements such as Sc and La (B. R. Berger, unpublished data, 1984). All of the vein deposits contain the association Ag-Cu-Pb-Zn-Sb-As and sporadically detectable Bi, Cd, Sn, and W; porphyry-type deposits, however, are geochemically distinguishable

from vein-type deposits by the suite of La-Mo. The molybdenum porphyry-type deposits also show an association of Ag-Cu-Pb-Zn-Sb-As but show Mo-La as well. Sc and Mn are important discriminators of tungsten-bearing skarn deposits and distinguish them from the porphyry and vein-type deposits.

3. Because of the interrelation between porphyry-type and vein-type deposits in batholithic terranes, geochemical exploration models must be based on interconnected deposit types. A general geochemical model for vein-type and related molybdenum porphyry-type hydrothermal systems might be (1) spatial association with leucogranties or quartz rhyolite porphyry, both often anomalous in beryllium; (2) the association of Mo, Sn, and W with Ag, Cu, Pb, and Zn; and (3) trace-element zoning from the interior to the exterior as follows: Mo-Nb-Sn-W-La, Cu-Ag-F, Pb-Zn, As-F, Ba, and Mn-Ba (Siems and others, 1979).

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CRATER, CALIFORNIA: A CASE STUDY OF APPLIED GEOCHEMICAL MODELING TECHNIQUES

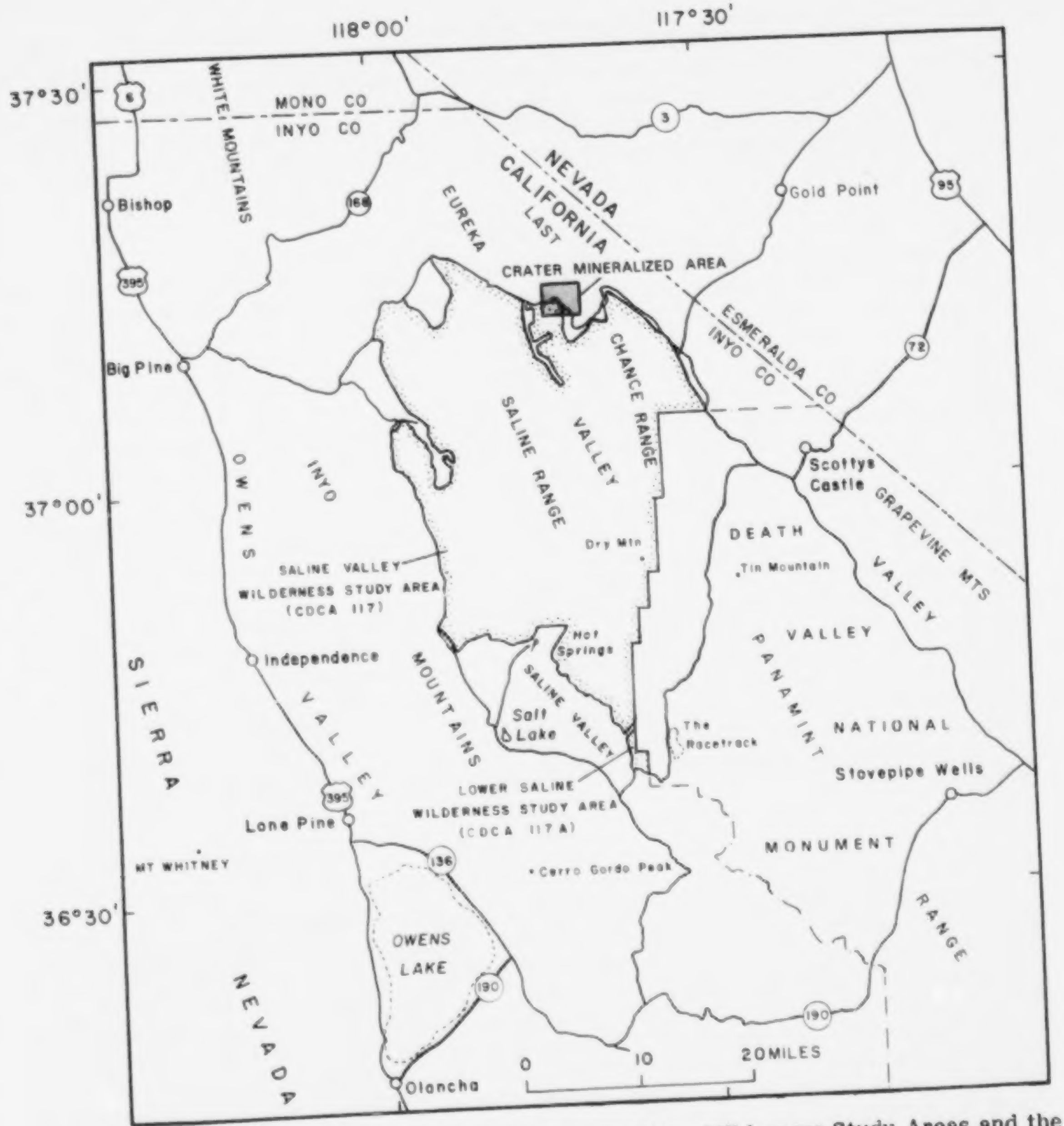
By Sherman P. Marsh

Abstract

The mercury-sulfur-gypsum mineralizations at and in the vicinity of Crater, Calif., have long been recognized by geologists and geochemists, but little has been written to explain these occurrences in the context of modern genetic and ore deposit models. Geologic and geochemical studies in the region have indicated that these mineralizations are the consequence of geothermal activity and that certain features shared by the hydrothermal system and current models of hot spring-type precious-metal deposits suggest potential for buried epithermal precious-metal mineralization at Crater.

Introduction

The Crater mercury-sulfur-gypsum mineralized area is located in east-central California along the crest of the Last Chance Range, northwest of Death Valley (fig. 1). The area, between long 117°39' and 117°45' and lat 37°10' and 37°15', varies in elevation between 5,000 and 6,000 ft above sea level. Relief is generally moderate but can be extreme. The climate is arid, and there are no active streams in the area. Although precipitous range fronts incised by many steep canyons occur on the eastern and western sides of the area, the range crest is an area of relatively low relief occupied mostly by a shallow basin. The old abandoned town and mine site of Crater lie in this shallow basin. Access to the Crater area is by a partially paved, partially dirt road that runs from Big Pine, Calif., to the northern end of Death Valley National Monument. Mining activity at Crater, centered around sulfur and mercury, took place mostly in the early 1900's. At one time, Crater was the largest sulfur mine in California (Wrucke and others, 1984). All that remains now are several large open pits and some relic equipment. The abandoned El Capitan mercury mine is located about 2 mi north of Crater, and numerous prospect pits, small shafts, and bulldozer cuts dot the entire Crater area.



118°00'
117°30'
37°30'
37°00'
36°30'
6
MONO CO
INYO CO
WHITE MOUNTAINS
Bishop
168
3
NEVADA
CALIFORNIA
EUREKA
LAST
Gold Point
95
395
CRATER MINERALIZED AREA
ESMERALDA CO
INYO CO
72
Big Pine
CHANCE RANGE
SALINE RANGE
VALLEY
OWENS
INYO
Scottys Castle
GRAPEVINE MTS
DEATH
Tin Mountain
VALLEY
VALLEY
Dry Mtn
SALINE VALLEY WILDERNESS STUDY AREA (CDCA 117)
Hot Springs
Independence
MOUNTAINS
SALINE VALLEY
PANAMINT
SIERRA
VALLEY
Salt Lake
The Racetrack
NATIONAL
Stovepipe Wells
395
LOWER SALINE WILDERNESS STUDY AREA (CDCA 117A)
Lone Pine
136
MT WHITNEY
Cerro Gordo Peak
MONUMENT
RANGE
OWENS LAKE
NEVADA
190
190
0
10
20MILES
Olancha

FIGURE 1.—Location of Saline Valley and Lower Saline Wilderness Study Areas and the Crater area of mercury-sulfur-gypsum mineralization in Inyo County, California.

Attention was drawn to the Crater area during a regional mineral resource assessment of the Saline Valley Wilderness Study Area by the U.S. Geological Survey and the U.S. Bureau of Mines. The mineralization at Crater extends into the northeastern part of this area, which the U.S. Bureau of Land Management has proposed as a wilderness. Stream sediments and panned concentrates from stream sediments were routinely sampled during the springs of 1981 through 1983 as part of the Wilderness Program. Gold, silver, antimony, boron, beryllium, molybdenum, tin, lead, and zinc anomalies were detected, and cinnabar was seen in the concentrates from several drainages. These discoveries prompted a more detailed investigation that included the sampling of mineralized and altered rocks. The results of this regional study were published, and the area was assessed as having resource potential for gold, mercury, and sulfur (Wrucke and others, 1984). Work done under the Mineral Resources of Public Lands Program was used as a basis for more detailed studies in the fall of 1984.

Geology

The geology of the Crater area can be divided into two major terranes, one in the eastern part of the area and one in the western part. The eastern terrane consists of a section of relatively flat lying Paleozoic limestones, dolomites, and shales cut by north- to northwest-trending normal faults. The Carrara Formation (Lower and Middle Cambrian), the Bonanza King Dolomite (Middle and Upper Cambrian), the Nopah Formation (Upper Cambrian and Lower Ordovician), and the Rest Spring Shale (Mississippian) have been mapped in this area. The western terrane is separated from the eastern part by a series of north-south-trending normal faults and is uplifted to the west by these normal faults. The western terrane has also undergone extreme structural deformation caused by the Mesozoic (probably Jurassic) Last Chance thrust fault, which thrust Cambrian siliceous rocks over Mississippian shales, siltstones, sandstones, and limestones. The Zabriskie Quartzite (Lower Cambrian), the Carrara Formation (Lower and Middle Cambrian), and the Perdido Formation (Mississippian) have been mapped in this area. Cretaceous igneous rocks intruded this geologic section to the north and south of the Crater area. This structurally prepared ground provided a center for the Tertiary (Pliocene) hot spring activity and subsequent mineralization at Crater.

The mines and prospects of the Crater area are in large zones of sulfur, gypsum, and silica alteration that have replaced limestone in the Carrara Formation and the Bonanza King Dolomite. These zones are centered along major northeast-southwest- and north-south-trending faults and appear to have been the center for the hot spring activity.

Geochemical Studies

To identify the extent and type of mineralization present in the Crater area and to provide essential geochemical information about the major- and trace-element assemblages associated with this mineralizing system, 173 rock samples were collected. All samples were analyzed for 31 elements by a semiquantitative dc arc emission spectrographic method and for 9 elements by atomic absorption methods (Erickson and others, 1985). An interpretation of these geochemical data in the context of the geologic framework led to the proposition that two models were necessary to explain the data. The first model is the vapor-dominated part of a hydrothermal system as described by White and others (1971). The second is the hot spring deposition model from Berger and Eimon (1983) (fig. 2). Using these two models as guides, a schematic cross section of the Crater area depicts the theoretical resultant depositional model (fig. 3).

One of the most striking characteristics of the Crater area is the intense hydrothermal alteration. This alteration, consisting of a mixture of sulfur, gypsum, and siliceous sinter, is the result of processes related to the vapor phase of a hot spring system percolating upward through limestones and dolomites. Even in the most intensely altered areas, relict bedding and structures of the original limestone and dolomite are preserved. Near orifices and vents, silicification and microbrecciation are more intense. Throughout the Crater area, sulfur-, gypsum-, and silica-bearing sinter vents are found along major fault zones. These observations are consistent with the vapor-dominated hydrothermal system model described by White and others (1971), in which

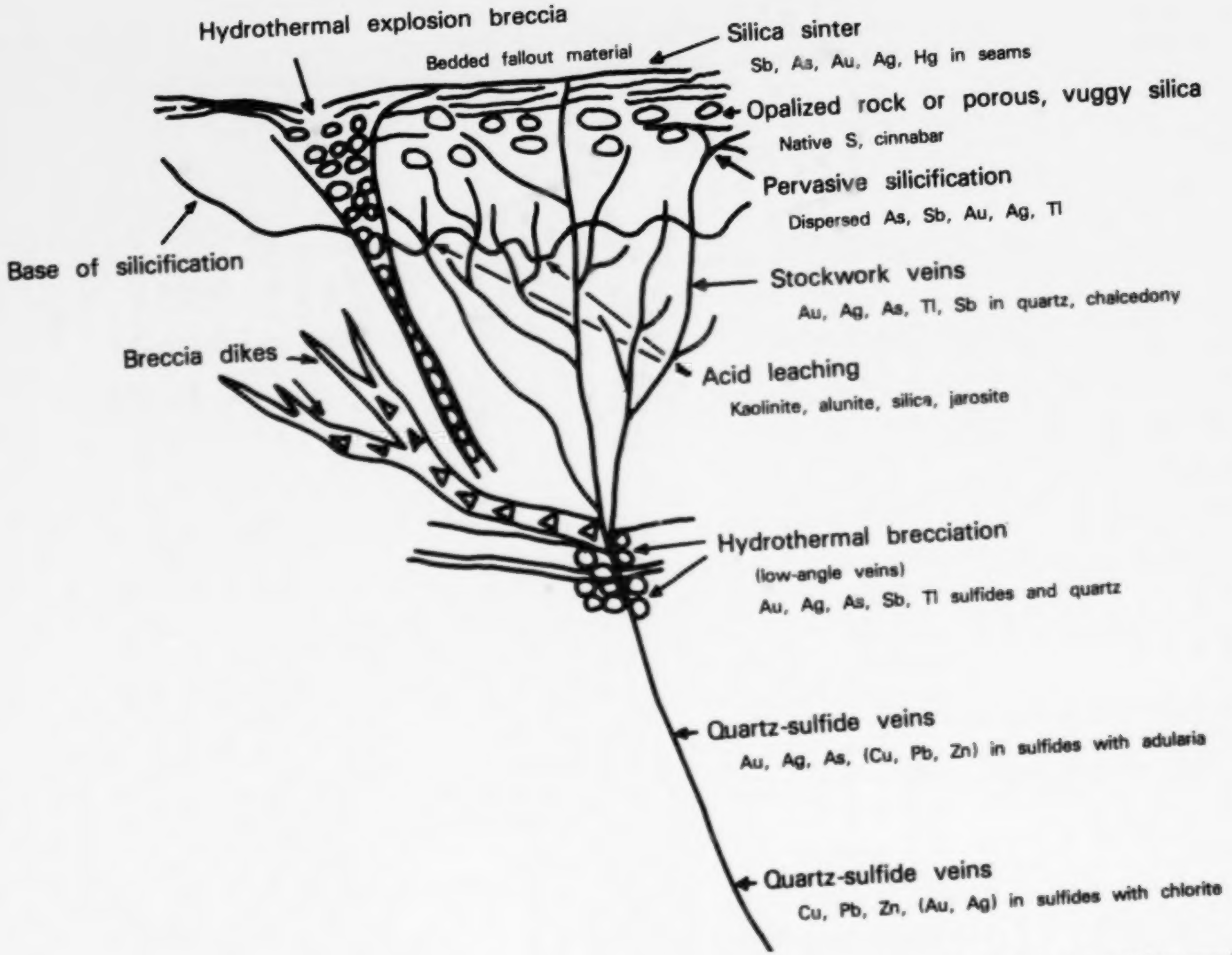

Hydrothermal explosion breccia
Bedded fallout material
Silica sinter
Sb, As, Au, Ag, Hg in seams
Opalized rock or porous, vuggy silica
Native S, cinnabar
Pervasive silicification
Dispersed As, Sb, Au, Ag, Tl
Base of silicification
Stockwork veins
Au, Ag, As, Tl, Sb in quartz, chalcedony
Breccia dikes
Acid leaching
Kaolinite, alunite, silica, jarosite
Hydrothermal brecciation
(low-angle veins)
Au, Ag, As, Sb, Tl sulfides and quartz
Quartz-sulfide veins
Au, Ag, As, (Cu, Pb, Zn) in sulfides with adularia
Quartz-sulfide veins
Cu, Pb, Zn, (Au, Ag) in sulfides with chlorite

FIGURE 2.—Schematic cross section (from Berger and Eimon, 1983) of the hot spring deposition model showing the spatial relations of alteration and trace-element geochemistry and some of the more important structural features of this deposit type.

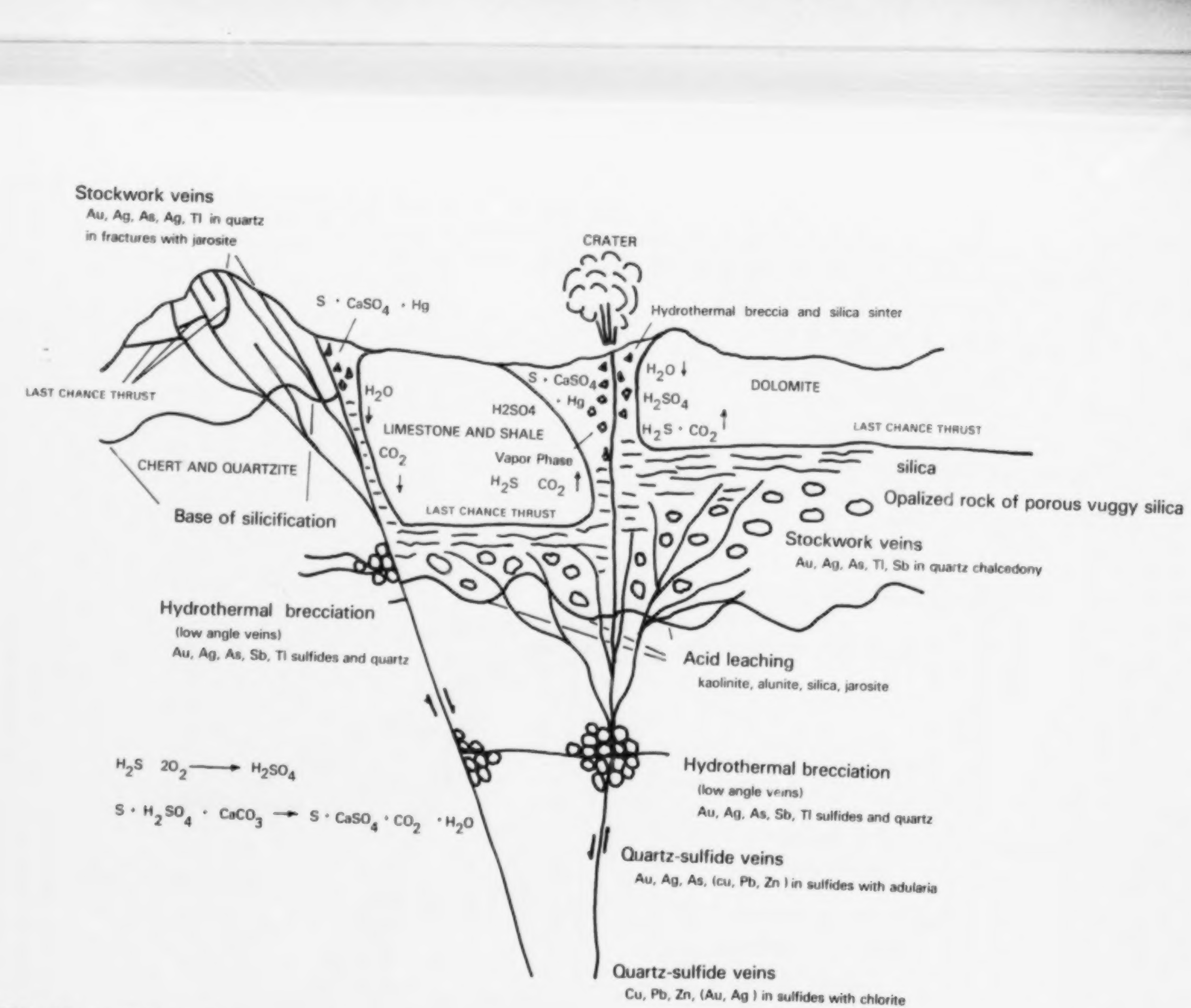

Stockwork veins
Au, Ag, As, Ag, Tl in quartz
in fractures with jarosite
CRATER
$S \cdot CaSO_4 \cdot Hg$
Hydrothermal breccia and silica sinter
LAST CHANCE THRUST
H_2O
$S \cdot CaSO_4 \cdot Hg$
H_2O
DOLOMITE
H2SO4
H_2SO_4
LIMESTONE AND SHALE
$H_2S \cdot CO_2$
LAST CHANCE THRUST
CO_2
Vapor Phase
CHERT AND QUARTZITE
H_2S CO_2
silica
LAST CHANCE THRUST
Opalized rock of porous vuggy silica
Base of silicification
Stockwork veins
Au, Ag, As, Tl, Sb in quartz chalcedony
Hydrothermal brecciation
(low angle veins)
Au, Ag, As, Sb, Tl sulfides and quartz
Acid leaching
kaolinite, alunite, silica, jarosite
H_2S $2O_2 \longrightarrow H_2SO_4$
Hydrothermal brecciation
(low angle veins)
Au, Ag, As, Sb, Tl sulfides and quartz
$S \cdot H_2SO_4 \cdot CaCO_3 \rightarrow S \cdot CaSO_4 \cdot CO_2 \cdot H_2O$
Quartz-sulfide veins
Au, Ag, As, (cu, Pb, Zn) in sulfides with adularia
Quartz-sulfide veins
Cu, Pb, Zn, (Au, Ag) in sulfides with chlorite

FIGURE 3.—Schematic composite cross section of the depositional model for Crater, Inyo County, California, showing spatial relations of alteration and trace-element geochemistry and some postulated structural features.

more water is boiled off than inflow can replace. Regions around these systems are high in sulfate and may be bleached and lacking in vegetation. The chemistry of rock samples taken from these highly altered areas is also consistent with this model, as they are depleted in gold, silver, arsenic, antimony, and tungsten and enriched in mercury. Mercury is often separated in these vapor-dominated systems because of its high volatility. The El Capitan mercury mine is located in an orifice from this type of system. Once a working model for the Crater hydrothermal system was established, at least from surficial evidence, the chemistry was examined to establish a model for potential mineralization. Initial examination of the trace-element chemical data indicated a possibility of two mineralization periods. The first (and earliest) was a base-metal assemblage of copper, lead, zinc, and molybdenum containing some gold and silver related to the Cretaceous igneous activity that is prevalent north and south of the Crater area. The second was the trace-element suite commonly found in gold deposits of arsenic, antimony, tungsten, and silver related to the geologically younger (Miocene?) Crater hydrothermal system.

Two distinct types of mineralization were identified in the field: (1) the highly altered areas of sulfur, gypsum, and siliceous sinter along faults in the eastern limestone-dolomite rocks and (2) mineralized fractures, faults, and veins in the western siliceous section. To help define the trace-element relations, the rock samples were divided into three groups: samples taken from predominately limestone-dolomite terrane, samples taken from predominately siliceous terrane, and samples taken from shales. Although the natures of these rocks are dramatically different, both geologically and chemically, the trace-element suites remained consistent, showing only some notable differences in intensity.

The Crater hydrothermal system is a vapor-phase system, which means that the trace-element anomalies for the suite associated with gold deposition in and around the sulfur-, gypsum-, and silica-altered areas are less intense in most metals, mercury being the exception. The fact that the base-metal suite is essentially absent in the sulfur-, gypsum-, and silica-altered rocks lends credence to the theory of two mineralization periods. Additional evidence for an earlier period of mineralization is that some of the north-south faulting in the eastern siliceous rocks (where the base-metal anomalies are most intense) extends to the north to the Cretaceous intrusive rocks.

Statistical Methods

The theories developed on the basis of field and laboratory evidence for the hydrothermal system and two mineralization periods were tested by applying statistical methods to the geochemical data. The geochemical data and descriptive geologic information were entered into a computer-based file called the Rock Analysis Storage System (RASS). Any or all of this information can be retrieved and converted into a binary form (STATPAC) for computerized statistical analysis (VanTrump and Miesch, 1976; U.S. Geological Survey, 1984).

Histograms were generated for geochemical suites in limestone-dolomite, siliceous, and shale rocks. Because the sampling program was biased toward mineralized and altered material, the histograms were used mainly to demonstrate the relative intensity of anomalies (potential mineralization) and the general distribution of values.

After the histograms were generated, R-mode factor analysis was run on the three rock data sets. The 10 factors generated for each data set accounted for 86 percent of the variance in the limestone-dolomite and shale data sets and 76 percent of the variance for the siliceous data set. Three observations were common to the three rock data sets: (1) the gold suite was present as a discrete factor, (2) the base-metal suite was present as a discrete factor, and (3) mercury was generally in a factor by itself, although, in other areas, it is commonly found as part of the gold suite. These observations helped to confirm that there were two mineralization periods in the Crater area and that the hydrothermal system at Crater was vapor dominated.

Factor analysis for the limestone-dolomite rocks showed the most complete elemental suite related to the hot spring depositional model for gold (Berger and Eimon, 1983); this elemental suite included gold, silver, arsenic, antimony, and iron with copper and molybdenum. Other factors included suites of mercury and antimony and the base metals, a suite representing residual igneous source rocks, and a suite that indicated limestone-dolomite rocks.

Factor analysis for the siliceous rocks showed a base-metal suite, which was slightly more complex because of the introduction of antimony, and a gold suite that was less complex, containing only iron, gold, and arsenic. The factor for residual igneous rocks is more complex than that for the limestone-dolomite rocks; a high-temperature suite of bismuth, tungsten, yttrium, and zirconium indicates a stronger influence from an igneous source. Most of the siliceous rocks were collected from fault and fracture zones in the western terrane, which was structurally deformed by the Last Chance thrust fault and intruded by Cretaceous igneous rocks to the north.

The factor analysis for shale rocks is the least conclusive of the three data sets, because shale rocks are intermixed with both the limestone-dolomite and the siliceous rocks and because there were only 28 samples in the data set. The shale rocks are a mixture of hydrothermally altered material containing less altered fractured material. The elemental suites in the factors are still discernible, however, and remain similar to the other rock data sets. Factors for the shale rocks include a very distinct base-metal suite; a shale suite that includes iron, chromium, nickel, strontium, molybdenum, and vandium; gold and silver; and arsenic.

Conclusions

Geologic field observations and geochemical data generated from rock samples have generated two theories to explain the mineralization at Crater, Calif. Crater represents a vapor-dominated mineralized hydrothermal system following the hot spring deposition model. The evidence supporting these two theories and the intensity of the gold suite of trace elements at the surface indicate a high potential for a significant gold occurrence at depth (at or near the zone of boiling for the hydrothermal system.)

Ongoing work at Crater will provide additional information and refine the proposed geologic and geochemical models for the mineralization. In time, a more definitive evaluation of the gold potential will result.

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U.S. VIRGIN ISLANDS: A CASE STUDY OF EXPLORATION GEOCHEMISTRY FOR MINERAL RESOURCE APPRAISAL

By Henry V. Alminas

Abstract

The U.S. Geological Survey is assisting the government of the U.S. Virgin Islands through a multidisciplinary program designed to provide the geologic information necessary for the effective planning of land development and resource management.

The initial phase of geochemical studies was designed to acquire a regional data base from which to (1) plan detailed onshore followup resource-related investigations, (2) provide a focus in the planning of offshore geologic activities, (3) define the commodities most likely to have economic potential, and (4) provide geochemical maps of value in land use planning.

Several significant results have arisen from the geochemical studies completed under this program:

1. Extensive areas of previously undocumented hydrothermal alteration and related mineralization have been identified on the islands of St. Thomas, St. John, and St. Croix.
2. Within these areas of extensive alteration, there are discrete sectors having mineral resource potential.
3. There is a high potential for a variety of different mineral deposit types, including gold, silver, tin, lead, zinc, and copper.

Introduction

Location and Geography

The U.S. Virgin Islands consist of three major islands (St. Thomas, St. John, and St. Croix) and about 50 smaller islands scattered mainly along the northern and southern coasts of St. Thomas and St. John. St. Thomas and St. John (the second and third largest islands) and their attendant islets are located some 40 mi east of Puerto Rico within an area delineated by lat 18°15'00" to 18°25'30" and long 64°38'30" to 65°06'00". St. Croix is located approximately 30 mi southeast of St. Thomas.

Climate and Vegetation

The climate in the Virgin Islands is maritime tropical. Temperatures generally average in the 80°F's and are highest in August and lowest in January, although the differential is only 5° to 7°F. The average annual rainfall is 50 to 60 in. at higher elevations and 20 to 30 in. at lower elevations. There is no well-defined wet or dry season.

Vegetation, which is generally not native to the islands, and consists of thorny brush and hurricane grass in formerly cleared areas. The uncleared portions and the more mountainous areas are covered by dense tropical forest characterized by few large trees and a dense undergrowth of brush and vines.

Geologic Setting

In a regional context, the Virgin Islands are part of the eastern portion of the greater Antilles island arc chain extending from Cuba in the northwest through Venezuela in the southeast. The rocks found here are an assortment of island-arc-related Cretaceous and Tertiary volcanic, volcanoclastic, carbonate, and plutonic rocks.

Geochemistry

As part of a regional geochemical study of the island, samples of outcrop, soil, and stream sediments were collected at an average density of four sites per square mile. Heavy-mineral concentrates were derived from the soil and stream-sediment samples. In addition, acid extractable metals (Alminas and Mosier, 1975) from the low specific gravity components (less than 2.85 sp gr using bromoform) of soils and stream sediments were analyzed by means of emission spectrography (Grimes and Marranzino, 1968). This approach was chosen in an attempt to enhance geochemical patterns that would be otherwise subdued because of the strong leaching of surficial materials in this tropical environment. The leached material consists primarily of iron and manganese hydroxide coatings on sand-sized grains of quartz and feldspar. These hydroxides effectively adsorb metals moving in aqueous solution within the surficial environment.

Conclusions

Interpreting the regional geochemical data in the context of the regional geology of the U.S. Virgin Islands and current ore deposit models has led to several important preliminary conclusions:

1. A new tin metallogenic province has been discovered on the U.S. Virgin Islands. The distribution of tin on the island of St. Croix is shown in figure 1.
2. The trace-element suite of Au-Ag-Te-Sn-Pb-Cu-Zn-Bi-Sb-Mo and the presence of cassiterite (SnO_2) after lead-tin sulfides, secondary copper-tin sulfide, and native tin suggest an analogy to the silver-tin veins found in Bolivia. A model for tin veins and replacements in carbonate terranes is shown in figure 2.
3. The trace-element geochemistry and stream-sediment mineralogy suggest the presence of unmapped acid intrusions, particularly on St. Croix.

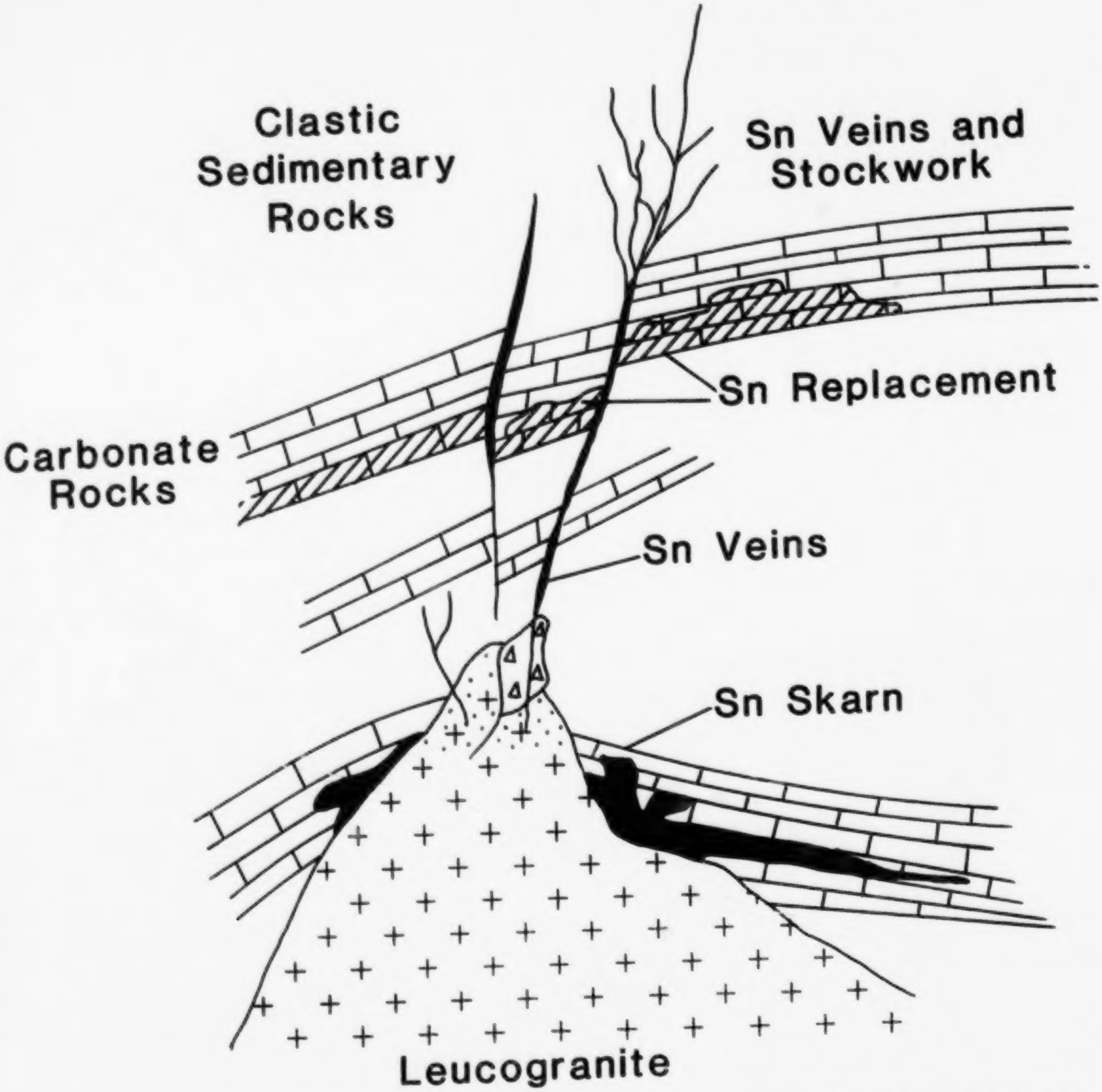
Clastic Sedimentary Rocks
Sn Veins and Stockwork
Sn Replacement
Carbonate Rocks
Sn Veins
Sn Skarn
Leucogranite

FIGURE 1.—Schematic model for tin veins and replacements in carbonate terrane.

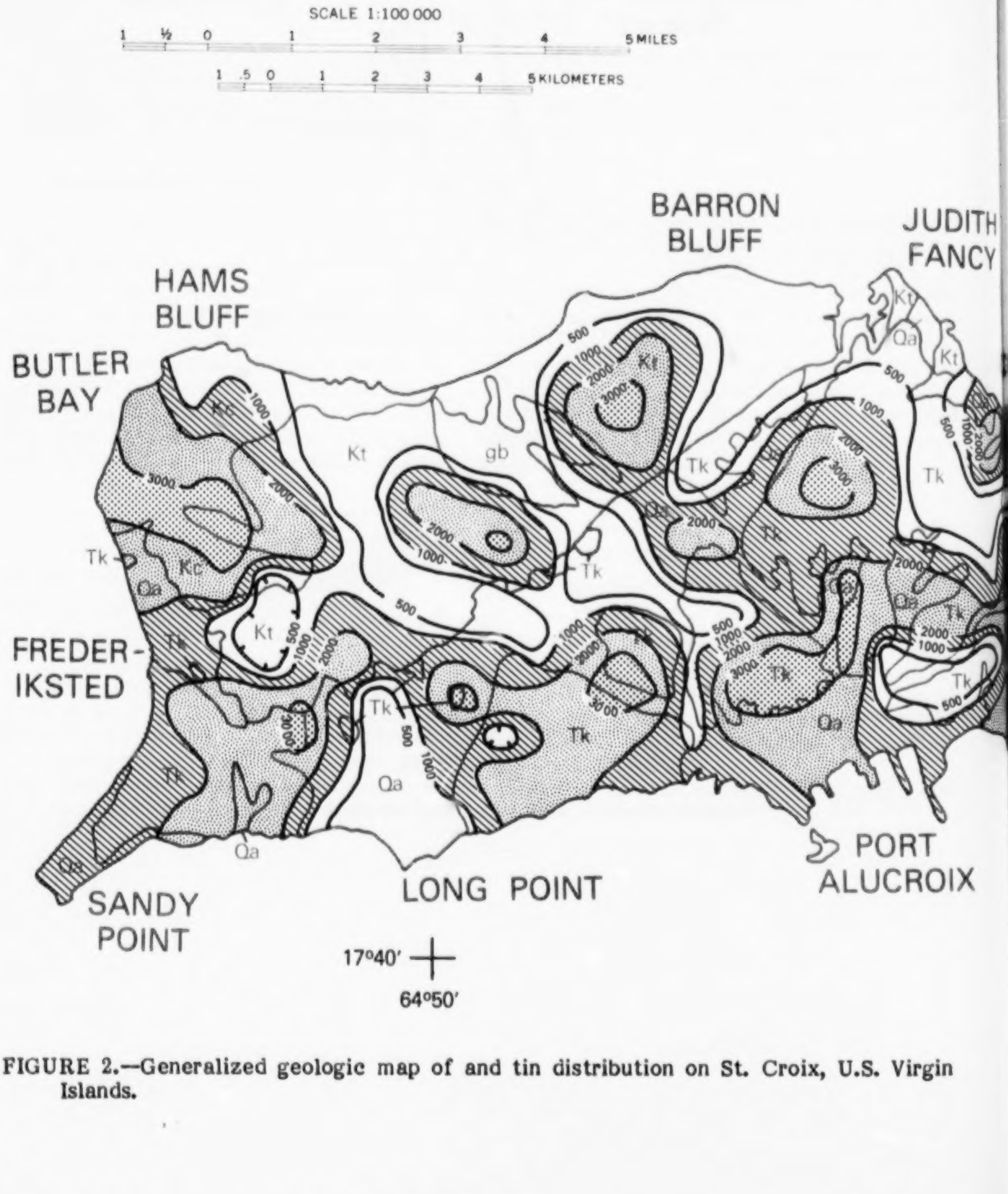
SCALE 1:100 000
1 ½ 0 1 2 3 4 5 MILES
1 .5 0 1 2 3 4 5 KILOMETERS
BARRON BLUFF
JUDITH FANCY
HAMS BLUFF
BUTLER BAY
FREDERIKSTED
SANDY POINT
LONG POINT
PORT ALUCROIX
Kt
Kc
gb
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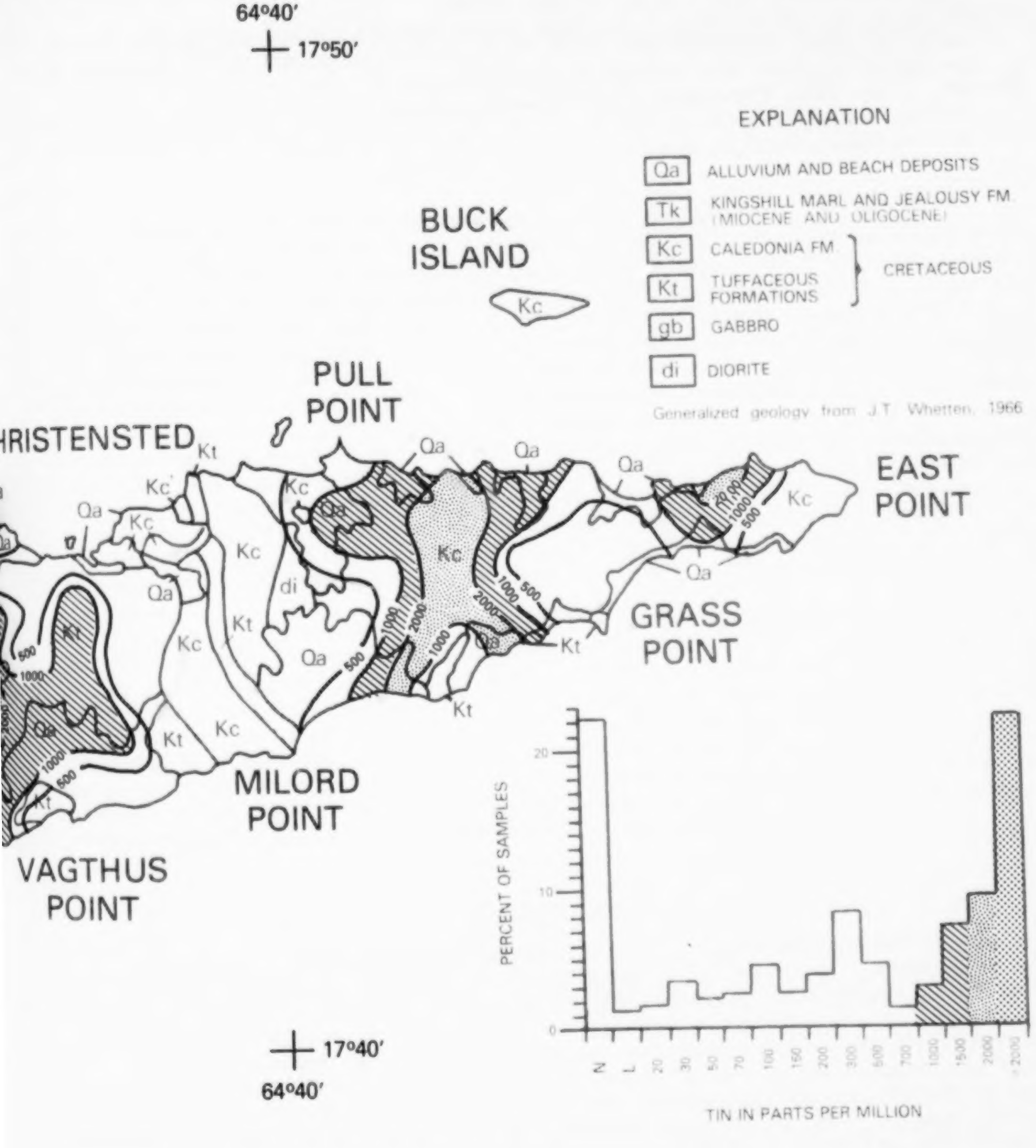
FIGURE 2.—Generalized geologic map of and tin distribution on St. Croix, U.S. Virgin Islands.


64°40′
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17°40′
64°40′
EXPLANATION
Qa ALLUVIUM AND BEACH DEPOSITS
Tk KINGSHILL MARL AND JEALOUSY FM. (MIOCENE AND OLIGOCENE)
Kc CALEDONIA FM.
Kt TUFFACEOUS FORMATIONS
CRETACEOUS
gb GABBRO
di DIORITE
Generalized geology from J.T. Whetten, 1966
BUCK ISLAND
PULL POINT
HRISTENSTED
EAST POINT
GRASS POINT
MILORD POINT
VAGTHUS POINT
Qa
Kc
Kt
di
500
1000
2000
PERCENT OF SAMPLES
0
10
20
N
L
20
30
50
70
100
150
200
300
500
700
1000
1500
2000
>2000
TIN IN PARTS PER MILLION

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GEOCHEMICAL ABUNDANCE MODELS: AN UPDATE, 1975 to 1984

By Robert G. Garrett
Geological Survey of Canada

ABSTRACT

Resource estimates for 10 Canadian metallic resources (Ni, Cu, Zn, Pb, Mo, Ag, Au, U, Sn and Cr), based on 1975 data and undertaken in 1977, have been updated to 1984. Major changes in the appraisal are limited to minerals whose values have increased (gold) or for which exploration activity has been expanded because of value and security of supply considerations (tin). For the metals with which Canada is well endowed (one of the world's major metallogenic belts passes through or occurs in Canada), the appraisal indicates resource amounts to be of the order of abundance (in percent) times 10^{10} t. Tin and chromium were selected in 1977 as examples of commodities with which Canada was not well endowed. The recognition that regions of Nova Scotia were once part of the European Hercynian-age tin province led to the discovery of the East Kemptville deposit, which has raised the tin endowment estimate by approximately an order of magnitude. Likewise, the reappraisal of chromite resources and the search for platinum have led to a doubling of the estimated chromium endowment. The update draws attention to how sensitive such resource estimates are to dates and information levels and to how changes in commodity value and exploration intensity can lead to significant changes in resource appraisals.

Two additional models are discussed, the Brinck log-binomial and the Agterberg lognormal models. A method of calibrating the Brinck model for local and regional use has been investigated. Explored past-producing or producing areas where the geochemistry and mineral resources are reasonably well known are used to determine critical parameters in the Brinck model. These parameters can then be used to develop estimates in geologically and metallogenically similar areas or to infer the properties of lower grade-larger tonnage resources in the same area or in similar areas. These two methods, which have several points of similarity, are described with the aid of examples from the Klondike alluvial goldfields and the Canadian Appalachians (zinc).

INTRODUCTION

McKelvey's (1960) crustal abundance model has not been used extensively as a tool for resource appraisals. Rather, it is accepted as a "quirk" of geochemistry and economics that holds true on a global scale or for regions or nations large enough to be regarded as valid samples of the geology and metallogeny of the globe.

McKelvey noted that an interesting and surprising relation exists between the minable reserves of various elements in the United States and the abundance of those same elements in the Earth's crust. He went on to show that reserves (in tonnes) were equivalent to the crustal abundance (in percent) times 10^9 to 10^{10}. Global studies, reported by Garrett (1978), indicated reserves to be of the order of 10^{10} to 10^{11} times as large as crustal abundance. The inference is that society puts a value on many metals and elements that is a constant function of their rarity. In other words, approximately 10^{-12} to 10^{-13} of the total amount of many elements in the crust is concentrated in a few localities, usually above the crustal abundance by factors of between 10^2 and 10^4, in such a way that it is extractable and usable because of the value that society places on those elements.

The major problem with the crustal abundance model is that it breaks down as smaller portions of the globe are considered. The value of a commodity is based on global considerations; thus, unless one of the world's metallogenic belts, from whence the commodity is produced, passes through or is within the region under consideration, it is unlikely that any significant reserves or potential resources will be identified. However, for Canada, which represents approximately 8 percent of the world's land mass, the crustal abundance model investigated in the 1970's (Garrett, 1978) indicated a situation that was consistent with the then-known placement of the world's major metallogenic provinces with respect to Canada's national boundaries.

This paper updates the Canadian crustal abundance model of 1975-76 to 1984-85 and discusses the reasons for significant changes. It also reviews two other geochemical models—the log-binomial model, used extensively in Europe by Brinck and his coworkers, and the lognormal model advanced by F. P. Agterberg in Canada. Although both these models can be used on a more local basis, underlying both is an assumption or acceptance of a lognormal model for the distribution of the less abundant metals in the Earth's crust. The paper closes with a short discussion of this topic, drawing on experiences gained in the last decade from broad-scale geochemical surveys undertaken around the world.

1984-85 CRUSTAL ABUNDANCE MODEL FOR CANADA

The present study follows very closely the methodology described for the 1975-76 study (Garrett, 1978). The crustal abundance estimates for Canada (table 1) were based on clarkes for various rock types in comparison with their relative abundance in Canada. The only change concerns gold, where the abundance has been revised downwards from 9 to 5 ppb. The 9-ppb estimate arose owing to sampling bias related to sandstones and conglomerates from gold-producing regions. The 5-ppb estimate derives from the work of Boyle (1979) and agrees more closely with generally accepted crustal abundance estimates.

TABLE 1.—Crustal abundance estimates for Canada
(All data from Garrett (1978), except those
for gold (Boyle 1979))

Element	Abundance, in percent	Estimate, in ppm
Ni----------------	4.7×10^{-3}	47
Cu----------------	3.1×10^{-3}	31
Zn----------------	6.0×10^{-3}	60
Pb----------------	1.4×10^{-3}	14
Mo----------------	1.2×10^{-4}	1.2
U-----------------	2.5×10^{-4}	2.5
Ag----------------	7.5×10^{-6}	.075
Au----------------	5.0×10^{-7}	.005
Cr----------------	6.2×10^{-3}	62
Sn----------------	2.3×10^{-4}	2.3

The present study presents Canadian reserve estimates as cumulative on past production and thus defines the sum of the metals known to exist as "exploitable" in Canada. The past production and reserve figures are further extended to include surmised resources in areas of production or past production that might reasonably be prognosticated on geologic grounds and would be exploitable through current technology if they were delineated. The various data sources used as a basis for resource estimates of the commodities, nickel, copper, zinc, lead, molybdenum, uranium, silver, gold, chromium, and tin are given in table 2, together with cumulative totals.

The relation between crustal abundance and resources is illustrated in figure 1, which plots past production, reserves, and surmised resources against crustal abundance. The most notable feature of the plot is the clustering of the cumulative to surmised resources data for nickel, copper, zinc, lead, molybdenum, silver, and gold within half an order of magnitude of abundance (in percent) times 10^{10}. These metals, together with uranium, are all commodities for which at least one of the world's major metallogenic provinces falls within Canada's boundaries. A further interesting feature is that the commodities having the longest histories of exploration and mining also have the highest cumulative resources. Mining for copper, zinc, lead, silver, and gold all commenced in the 1890's, for molybdenum in the 1920's, and for uranium in the 1940's. Now, in the mid 1980's, tin mining is underway; this tin is being produced on the basis of its own value rather than as a byproduct. It may be fortuitous, but, as the lengths of exploration and production histories have increased, so have cumulative resources, as

TABLE 2.—Past production, reserves, and resources for Canada, 1984
(All values in tonnes)

Element	Past production for 1900-1984	Cumulative to reserves (1984)[2]	Cumulative to surmised resources[2]	Data source[3]
Ni-----------	9.05×10^6	1.64×10^7	2.44×10^7	1, 2, 3
Cu-----------	2.36×10^7	3.98×10^7	6.07×10^7	1, 2, 3
Zn-----------	3.13×10^7	5.78×10^7	6.96×10^7	1, 2, 3
Pb-----------	1.33×10^7	2.24×10^7	2.59×10^7	1, 2, 3
Mo-----------	2.52×10^5	2.97×10^5	1.15×10^6	1, 2, 3
U[1]-----------	1.73×10^5	4.06×10^5	6.89×10^5	1, 4
Ag-----------	7.03×10^4	7.33×10^4	1.00×10^5	1, 2, 3
Au-----------	6.78×10^3	7.94×10^3	1.00×10^4	1, 2, 3, 5
Cr-----------	7.46×10^4	-	1.46×10^6	1, 7, 8
Sn-----------	1.17×10^4	2.56×10^5	4.04×10^5	1, 2, 6

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[1] Production data include 1984, but reserve and resource data available for 1983 only.

[2] Quoted in recoverable metal at the smelter.

[3] 1, Garrett (1978); 2, Energy, Mines and Resources (1976-85); 3, Lemieux and Jen (1985); 4, V. Ruzicka (personal communication, 1984); 5, R. I. Thorpe (personal communication, 1985); 6, W. D. Sinclair (personal communication, 1985); 7, R. F. J. Scoates (personal communication, 1985); 8, J. M. Duke (personal communication, 1985).

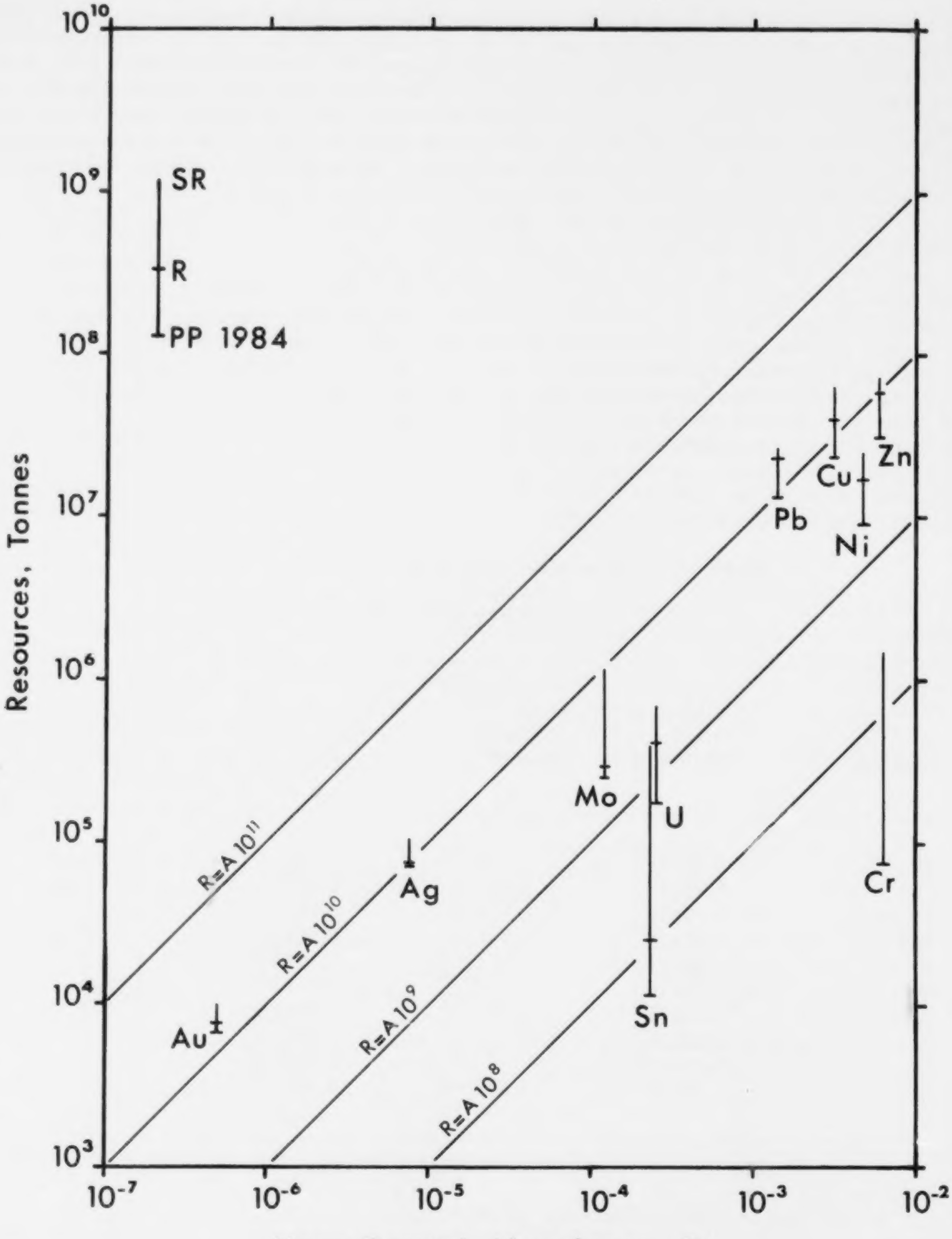

FIGURE 1.—Crustal abundance model for selected Canadian commodities. PP 1984 indicates past production; R, reserves; SR, surmised resources; A, abundance (in percent).

defined here. The simple extension of this correlation is that continued search in known mining camps and for new mining camps, driven by an appropriate value incentive, could delimit additional resources of many metals, particularly if their metallogenic provinces occur in Canada, they are "young," and they have short exploitation histories.

A comparison of the 1975-76 model with the current model shows that the most significant changes have been for gold, uranium, tin, and chromium. Apparent changes for the remaining metals are largely due to the fact that, in the current model, resources are cumulated only to the surmised level. Gold mining in Canada has benefitted from a very extensive exploration effort and from new mines in Ontario (Hemlo district) and the Northwest Territories (Lupin). In the 1975-76 model, gold mining in Canada was considered to be past its prime. Now, however, the situation has changed radically, owing to fluctuations in the price of gold—from $160 (U.S.) in 1975 to a peak of $850 in early 1980 back to $440 in 1985. Perhaps these price variations are the most convincing proof that, if the price is right, geologists and prospectors can deliver the deposits to the engineers' doorsteps.

Uranium has suffered from price decreases; as a result, lower grade ground once considered a resource is currently not considered to be exploitable. The most significant change between the 1975-76 model and the current model involves an order-of magnitude increase in the resource amount of tin. In the late 1970's, it was recognized that parts of Nova Scotia could have been within the broad limits of the western European Hercynian tin province before the development of the Atlantic Ocean in Jurassic time. A concerted exploration effort by Shell Minerals led to the discovery of the East Kemptville deposit, which contains a total of 86×10^3 t of tin slated for exploitation over the next 17 years. The production from this mine alone will just about meet Canada's annual tin consumption, about 2.5 percent of global use (King, 1985). The effect of East Kemptville on the tin resource model demonstrates the time-dependant nature of resource estimation and the importance of recognizing the presence of parts of global metallogenic provinces within national boundaries.

Chromium resource estimates have increased some twofold owing to exploration efforts aimed not directly toward chrome but towards the platinoids. In particular, unconfirmed reports indicate that INCO's exploration program in the Big Trout Lake area of northwestern Ontario may have unintentionally doubled Canada's chromium resources.

The 1975-76 crustal abundance model selected tin and chromium as contrasting elements, since it was not believed at the time that Canada was well endowed with either. Time, exploration knowledge, and effort, together with metal prices, have shown that these presumptions were not entirely true. It will be interesting to reassess the situation in 10 years to see what further changes have taken place.

LOG-BINOMIAL MODEL

As an earlier section pointed out, the traditional crustal abundance model fails as smaller regions of the Earth's crust are considered. The log-binomial model has been considered for use in Canada on a more local scale, particularly where binomial-like processes have seemed conceptually acceptable from an ore genesis viewpoint.

The log-binomial model has recently been reviewed by Harris (1984), who traced the development of the model from de Wijs' (1951) work through various extensions of that work by Brinck (1974, 1976). In its simplest form, the log-binomial model considers a volume of crust containing a fixed amount of an element, the volume is repeatedly halved, and the element is divided between the halves according to a rule that results in concentration in one half and depletion in the other. Repeated applications of this procedure result in a positively skewed log-binomial distribution, which, if it is taken ad infinitum, leads to a lognormal distribution of the element between all the subunits generated by the binomial process. Figure 2 illustrates the first three steps of such a

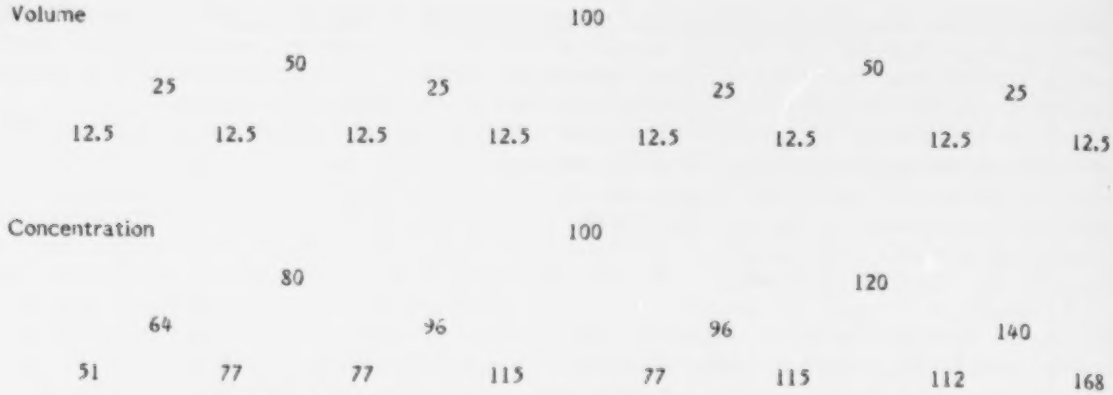

FIGURE 2.--First three stages of a log-binomial process.

log-binomial process; at each step, the concentration is increased or decreased by 20 percent. As figure 2 shows, even after three steps, the distribution has already taken on a positive skew. The mean is still 100, and the minimum value is 51, whereas the maximum is 168, equivalent to a 19-percent increase is skew or asymmetry. Clearly, such models can generate ore grade concentrations from crustal abundance levels, given large enough binomial processes and appropriate concentration efficiencies (for example, 20 percent).

The mass of an element is redistributed into a series of blocks of equal masses and varying concentrations. If M tonnes is the total mass of rock present and is the order of the binomial, then the mass m_k of the blocks of different concentrations is defined for any particular stage of the binomial k through the binomial coefficient ${}^{\alpha}C_k$:

$$m_k = {}^{\alpha}C_k \cdot M \cdot 2^{-\alpha}$$

The actual mass of the element r at the same kth stage derived from the total mass M having a crustal abundance A (in parts per million) of the element in question is

$$r_k = m_k \cdot A \cdot 10^{-6} \cdot (1+q)^{\alpha-k}(1-q)^k$$

where q is the efficiency of the binomial process in concentrating an element expressed as a proportion (for example, 0.2). It can thus be seen that the total amount R (in tonnes) of an elements in a homogeneous block is redistributed as follows:

$$R = \sum_{k=0}^{\alpha} {}^{\alpha}C_k R \; 2^{-\alpha}(1-q)^{\alpha-k}(1-q)^k$$

The major problem in using the log-binomial model is estimating appropriate values for the order of the binomial α and its efficiency q. The various procedures proposed for estimating α and q have been reviewed by Harris (1984). Since the Geological Survey of Canada was interested in generating local models that could be used in regional resource assessment studies rather than in projects on a global or a national scale, a different procedure has been investigated.

First, given a crustal abundance A (in parts per million), it is possible to compute the maximum concentration b (in parts per million) that any particular α-q pair will generate:

$$b = A(1+q)\alpha$$

The maximum concentration can be considered a barrier concentration that is chosen for a particular deposit type or region. For example, the copper content of chalcopyrite is approximately 35 percent (350,000 ppm), or the uranium content of pitchblende approaches 84 percent (840,000 ppm). Given the concentrations A and b, values of q can be computed dependent on α:

$$q=(b/A)^{\alpha^{-1}}-1$$

Therefore, a range of binomial orders α can be selected and a value of q computed that will lead to the generation of one block in the binomial model of barrier grade.

Second, in modeling, an analogous training area is selected where the resources are acceptably defined in terms of tonnes of an element above a stated cutoff grade. A series of log-binomial trials are then undertaken for the range of α-q pairs selected, and the tonnage of that element above the defined cutoff grade is determined for each trial. The model selected is simply the α-q pair that gives the minimum difference between computed tonnes above cutoff and known resources. In other studies, described by Ruzicka (1976) and carried out before the procedure described above was fully developed, the crustal abundance estimate was varied in accordance with various models for the source area of the Elliot Lake uranium deposits. The selected α-q pair was then used as a resource model for Elliot Lake and similar regions in Ontario.

A selected log-binomial model can be used in two ways. First, it can be used to infer properties of the grade-tonnage relation in the model area for lower grade, larger tonnage resources; second, it can be extrapolated into areas of analogous geology elsewhere.

An example of the first type of investigation is the Klondike alluvial gold field study, which was motivated by the large, low-grade resource postulated to exist in the White Channel gravels. The Klondike has been producing gold since the rush of 1897-98, and the rich deposits in the valley bottoms and terrace gravels have probably all been discovered. Therefore, it is reasonable to treat the Klondike district as a good example where the high-grade resources are largely exploited, and the total metal produced having an appropriate assumed cutoff could lead to a useful model. The traditional genetic model for the Klondike goldfields is one in which gold in the original Klondike Schist was concentrated into quartz veins during metamorphism. Following peneplanation in Tertiary time, erosion concentrated gold into the White and Yellow Channel gravels. Initially, the gold was preferrentially concentrated into the White Channel gravels; rejuvenation of the drainage systems concentrated it again into the terrace gravels and valley bottoms, where it has been extensively mined.

Tyrell (1912, p. 58) estimated that the White Channel gravels had been produced from some 900 ft (275 m) of erosion over an area of 800 mi^2 (2,070 km^2). He stated, "One hundred and thirty-six cubic miles of this gold bearing rock were put through nature's mills and the gold contained in it was concentrated in nature's sluices...." Boyle (1979) reported the production as 10x10^6 oz, equivalent to 311 t, of a maximum fineness of 890. It is quite possible that this production estimate is low, since it is very likely that a lot of gold left the district without ever having been reported. R. W. Boyle (personal communication, 1984) believed the effective cutoff for the deposits over a history spanning some 70 years (from rush-day placer mining to the close of dredge operations) to have been 0.5 ppm (approximately 0.02 oz/yd^3 at a specific gravity of 1.5). Using these parameters and assuming an initial crustal abundance of 5 ppb yielded the following log-binomial model:

Mass of rock------- 1.517x10^{12} t (568 km^3 at 2.67)
Abundance---------- 5 ppb
Resource----------- 311 t
Maximum fineness-- 880
Cutoff------------- 0.5 ppm

The optimal values of binomial order and concentration efficiency were determined to be α=131 and q=0.156.

As the discussion above pointed out, there is some uncertainty as to the amount of gold actually produced from the Klondike district. If we assume that the actual amount was a third larger than what was reported (that is, 415 t), then the optimal values of a and q are 125 and 0.164, respectively, not greatly different from those determined for the reported tonnage.

The distribution of grades and block metal contents indicate that the geometric mean would be 1 ppb Au and that the mode of the metal content (the maximum amount of gold preserved in blocks) is approximately 20 ppb (fig. 3). However, owing to erosional and alluvial processes, much of this low-grade material has been removed from the Klondike district by the Yukon River. What is more interesting are the grades and tonnages just below the cutoff of 0.5 ppm and the relation that they may have to the White Channel gravel resource. The log-binomial model steps covering the possible range of the White Channel resource (0.1-0.5 ppm), together with the tonnages of both resource and host, are presented in table 3. The steps of particular interest are 82 to 85, in which the total mass of host rock is some 3.45×10^9 t. This value is approximately 25 percent greater than Boyle's (1979) estimate for the White Channel gravels remaining in situ. The model indicates the availability of some 851 t of gold at a bulk grade of 0.25 ppm, corresponding to approximately 0.01 oz/ton, which is the grade quoted by Boyle (1979).

The second example involves a model for Canadian Appalachian base-metal resources discussed by Agterberg and Divi (1978). The motivation behind this study was to draw comparisons with Agterberg and Divi's work and to develop a model that could be extrapolated to analogous Phanerozoic volcanic massive sulfide-bearing terranes. The

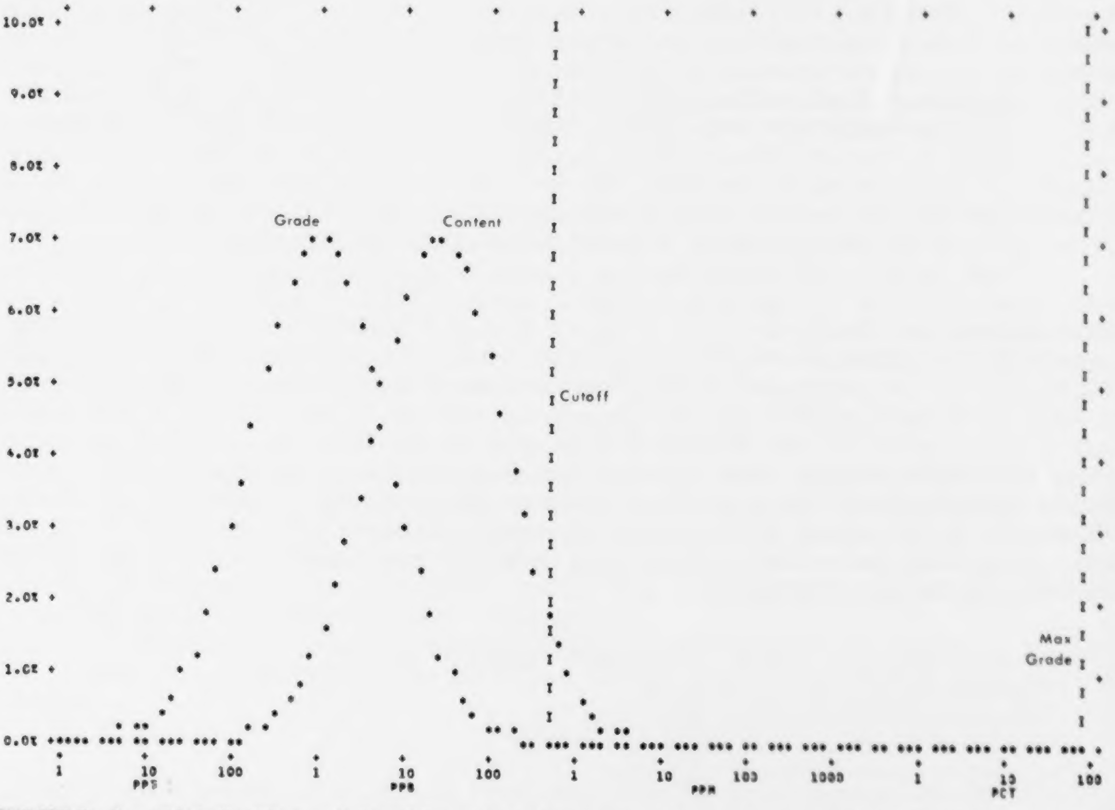

FIGURE 3.—Distribution of log-binomial block grades and contents for the Klondike alluvial gold model.

TABLE 3.—Log-binomial model for the Klondike alluvial gold field

Order step	Volume, in km^3	Mass, in t	Grade, in ppm	Content, in t
		Proposed model		
0	2.09×10^{-35}	5.57×10^{-26}	0.0001	6.35×10^{-44}
.				
.				
66	39.4	1.05×10^{11}	.0012	123
.				
.				
80	1.59	4.25×10^{9}	.095	405
81	1.00	2.68×10^{9}	.13	349
82	.611	1.63×10^{9}	.18	291
83	.361	9.64×10^{8}	.24	236
84	.206	5.51×10^{8}	.33	184
85	.114	3.04×10^{8}	.46	140
86	.0610	1.63×10^{8}	.63	102
87	.0315	8.42×10^{7}	.86	72
.				
.				
95	4.60×10^{-3}	1.23×10^{5}	10.6	1.31
.				
.				
131	2.09×10^{-35}	5.57×10^{-26}	87.4[1]	4.87×10^{-26}
		White Channel Gravel submodel		
82-85	1.29	3.45×10^{9}	0.25	851

[1] In percent.

Canadian Appalachian area covers some 0.362×10^6 km^2; and a section of crust 1 km deep yields 0.977×10^{15} t of rock at a specific gravity of 2.7. For the zinc model a crustal abundance of 94 ppm was assumed, together with a barrier grade of 67.1 percent, which corresponds to sphalerite. The resource modeled was 14×10^6 t of zinc having a cutoff grade of 5 percent; optimal values of a and q were determined to be 34 and 0.298, respectively.

This model has been used to investigate the effects of changes in area and crustal abundance on estimates of zinc resources. The effect of area changes is simple—the resource amount varies proportionately. Changes in crustal abundance lead to more complex situations, because, if the barrier grade is to be maintained, either q or a must change. As an example, if the area to be extrapolated to is the same size as the Canadian Appalachians and the crustal abundance is perturbed by 10 ppm (<11 percent), the effect on α and q are shown in table 4, where q is held constant in the upper half and α is held constant in the lower half. The results can also be viewed in terms of a sensitivity study for the Appalachian zinc model, in which the area, cutoff grade (5 percent), and the maximum allowable grade (67.1 percent) have been held constant. Clearly, if the concentration efficiency q is held constant (table 4, upper half) while crustal abundance is changed, poor models develop owing to the inability of the permissable changes in binomial order α to generate appropriate barrier grades. In the example, this procedure leads to changes of up to 60 percent in the resource estimate above the cutoff grade. On the other hand, if the binomial order α is held constant (table 4, lower half) while crustal abundance changes, the barrier grade can be well approximated, and resulting resource estimates above the cutoff grade vary by less than 4 percent. When the quality of other estimates and other assumptions in the model are considered, 4 percent is trivial and leads to the conclusion that the model is relatively insensitive to crustal abundance changes of the order of 10 percent. Thus, it can be seen that it is preferable to hold the binomial order α constant and let the concentration efficiency q vary with crustal abundance to maintain appropriate barrier grades.

The log-binomial model has limitations in extrapolating resource estimates for different cutoff grades (table 5). The model is discrete, and, if the binomial order is low, the average grade of generated blocks changes rapidly. In the case of the Appalachian zinc model, which has an order of 34, the result is invariance in the resource estimates in the worst case (for example, between 5 and 4 percent cutoff grades) or large jumps between estimates (table 5). It is interesting to note the general similarities between the log-binomial estimates and those of Agterberg and Divi (1978), shown in parentheses in table 5. The difference at the 5 percent cutoff is trivial, but, at 3 percent, the log-binomial model infers that the resource is 25 percent greater. It must be remembered, however, that the two models are not quite the same. The log-binomial considers a 1-km

TABLE 4.—Sensitivity of resource estimates to crustal abundance

Crustal abundance, in ppm	Concentration efficiency (q)	Binomial order (α)	Barrier grade, in percent	Resource in blocks having >5 percent Zn, in tx10^6
		q held constant		
84————————	0.2351	42	59.7	12.9
94————————	.2351	42	66.8	14.4
104————————	.2351	41	59.8	22.9
		α held constant		
84————————	0.2385	42	67.1	13.9
94————————	.2351	42	66.8	14.4
104————————	.2322	42	66.9	14.9

TABLE 5.--Resource estimates as a function of cutoff grade and crustal abundance

Crustal abundance, in ppm	Resource, in tx10^6 of zinc by cutoff grade		
	5 percent	4 percent	3 percent
84------------	13.9	13.9	56.1
94------------	14.4 (15.2)[1]	14.4	58.3 (43.3)[1]
104------------	14.9	14.9	60.5

[1] Value in parentheses from Agterberg and Divi (1978).

thickness of crust, whereas Agterberg and Divi considered a 200-m thickness. If, in fact, the increased resource defined by the log-binomial model occurs at depths of greater than 200 m, the combination of lower grade and increased depth will increase mining costs and render the resource commercially unexploitable in the foreseeable future. In comparison, the Klondike gold model (table 3), which has an order of 131, has relatively fine, discrete grade steps.

LOGNORMAL MODEL

The lognormal model mentioned in the previous section is the ultimate product of the log-binomial process. As the earlier discussion showed, the continuous nature of the lognormal model relative to the log-binomial model has advantages in the initial modeling of a known resource and in extrapolating to different cutoff grades. One significant difference between the two models is seen in the volumes of rock considered. The log-binomial model "processes" a volume of rock that could have provided the metals for one or more ore deposits. As a result, the log-binomial model can consider depths that are beyond the limits of mining. In contrast, the lognormal model considers only a volume that might reasonably be expected to be minable, and the distribution considered is that of minable blocks. The Appalachian log-binomial model presented in this paper considers a 1-km depth, whereas Agterberg and Divi (1978) considered a 200-m thickness in the development of their lognormal model.

The specific procedures used for the lognormal model have been presented by Agterberg and Divi (1978). Given the cumulative grade distribution (that is, the number of tons of ore of specified grade above a specified grade), the crustal abundance, the total weight of rock being considered, and tables for the extreme values of the normal distribution, the variance of the assumed lognormal distribution can be determined. For example, at a 5-percent cutoff, 174×10^6 t of ore is the stated resource. The total mass of rock being considered is 0.1954×10^{15} t (that is, a 200-m-thick layer having a specific gravity of 2.7 over an area of 0.3618×10^6 km^2). The fraction of the total mass that the ore represents is 8.906×10^{-7}. In terms of a normal distribution this proportion corresponds to the area under the normalized gaussian curve from 4.777 units to infinity. From this point, the estimation of the standard deviation is simple arithmetic:

$$z=(x-\mu)/\sigma$$

where z is the standard normal deviate (for example, 4.777), x is the cutoff grade, μ is the mean of the lognormal distribution, and σ is its standard deviation. The relation between the crustal abundance A and the properties of the underlying assumed lognormal distribution is defined by

$$A=\exp(\mu+0.5\sigma^2)$$

or

$$\ln A=\mu+0.5\sigma^2$$

Substituting for μ and assuming a lognormal model, we have

$$\sigma z=\ln x-\ln A+0.5\sigma^2$$

which leads to the solution for σ :

$$\sigma=z-(z^2-2\ \ln x+2\ \ln A)^{0.5}$$

In the present example, z=4.777; the cutoff is 5 percent, and the crustal abundance is 94 ppm, corresponding to 10.8190 and 2.5433, respectively, in ln ppm units. When these values are substituted, σ is estimated as 1.5728.

As Agterberg and Divi (1978) showed, the population standard deviation σ can be estimated for various cutoff grades and a final estimate made by using the mean of selected values. Agterberg and Divi continued with a sensitivity study and showed that the estimates of σ are relatively insensitive to changes in the thickness of crust chosen and the crustal abundance estimate. It is interesting to note that the insensitivity to crustal abundance estimation is also a feature of the log-binomial model.

Once the parameters of the lognormal model have been estimated, the expected tonnages of ore above specified cutoff grades can be determined. Comparison of the observationally estimated tonnages with the expected tonnages would indicate the presence of as yet unidentified resources prognosticated by the lognormal model. As earlier discussions pointed out, the major advanage of the lognormal model over the log-binomial model is that it is continuous and thus greatly facilitates the estimation of resources for various cutoff grades.

REALITY OF LOGNORMALITY

A major concern in using both the log-binomial and the lognormal resource models is the validity of the assumption of lognormality. The geochemical literature of the 1950's contained a spirited discussion of this problem. Vistelius's (1960) paper provided a useful summary of earlier work and shed further light on the problem as a result of his own studies. Briefly, he concluded that lognormal distributions should more properly be referred to simply as positively skewed distributions. Such distributions arise as joint distributions (that is, the sum of many normal or other basic distributions such as Poisson distributions) when they are compounded across large areas, many rock types, and, most importantly, many geologic processes, each of which has its own characteristic associated distribution. It is a fortuitous coincidence that, when these skewed distributions are compared with normal or lognormal distributions, they appear more likely to have been drawn from a lognormal distribution. Thus, although the data appear to be lognormally distributed, such distribution must not be used as evidence for an underlying single lognormally controlled process.

In their paper on the lognormal model, Agterberg and Divi (1978) referred to a number of studies that support a lognormal model for the distributions of grades in mining blocks. The problem of validity arises when this distribution is extended to the whole crustal environment and to areas larger than the mine environs. Great care should be taken in extending a model based on a very small part of the upper tail of a global distribution to the total global distribution.

Since the 1950's, vast amounts of geochemical data have been acquired from regional surveys on many continents. These data indicate that, although the overall distribution in many surveys may appear to be lognormal, more detailed study shows that these individual distributions are more likely to be normal or at least nonskewed when the data are subdivided into groups on the basis of geology and other environmental factors In fact, the presence of skewed distributions in the subdivided data has proven to be good evidence for the presence of mineralization or complex geologic and environmental conditions (Garrett and others, 1980).

The acceptance of a lognormal model is a precondition to using the resource models discussed in the previous two sections. The validity of the lognormal model has been challenged by Skinner (1976), who has argued that the lognormal model is incorrect for geochemically scarce elements and that a bimodal model is more appropriate. Certainly, the data from extensive geochemical surveys provides a basis for rejecting a true lognormal model and, in turn, supports Skinner's hypothesis. If the bimodal distribution holds for these elements, then the use of these models to estimate tonnages of lower grade resources is unsupported and will result in progressively overly optimistic resource estimates as the grade drops.

CONCLUSIONS

The crustal abundance model continues to be of interest as a rapid means of making comparative resource estimates for large portions of the Earth's crust. The underlying control of the model is complex, since the crustal abundance is acted on by economic considerations involving global commodity prices and the value that global and local societies place on commodities. When the model is applied to any particular part of the world, care must be taken to interpret the results in terms of global metallogenic provinces and their intersection with the boundaries of the study area.

The log-binomial and lognormal models have been applied to smaller regions of the Earth's surface. The critical control in using these models is the acceptance of a lognormal model. Growing geochemical evidence points to the fact that, although lognormallike distributions are often observed, they are most likely joint distributions derived from many underlying processes characterized by a variety of distributions and not from a single lognormal process. For sufficiently small areas and geologic situations where an underlying log-binomial or lognormal model of the dominant process is acceptable, however, these models can yield informative results.

Like the crustal abundance model, the log-binomial and lognormal models can be easily and rapidly applied. The effort required to carry out the modeling is small in comparison with the time and effort required to compile the base data, which would have to be compiled in any case for a more detailed deposit modeling study. Therefore, the insight that these models can provide is worth the relatively small effort needed to apply them. Broader use of these methods would certainly help resolve the question of under what conditions and in what circumstances the models are most appropriate.

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NEW APPLICATIONS OF GEOELECTRICAL METHODS IN MINERAL RESOURCE ASSESSMENT

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U.S. Geological Survey

ABSTRACT

Effective application of geophysics in public mineral resource assessment programs is an essential but challenging task. Owing to limited time and funding, geophysical work is generally limited to reconnaissance studies and an occasional detailed study of a small area. Consequently, it is critical to select the most suitable method or combination of methods for a particular study. The primary methods used by the U.S. Geological Survey are aeromagnetics, gravity, and remote sensing, but a new trend toward using a number of geoelectrical methods is developing.

The value of using geoelectrical methods such as airborne and ground electromagnetics and induced polarization in detailed mineral exploration is well known. In applying geophysics to mineral assessment, however, the objective is mapping subsurface lithologies and structures that may indicate favorable hosts for mineralization, not defining specific targets. Some of the geophysical methods normally applied in detailed exploration to locate and define drilling targets can be used in mineral resource assessment programs at regional scales simply by expanding the spacing between measurements. An example is presented where flight-line spacing was increased in airborne electromagnetic surveys within the upper peninsula of Michigan to provide information on the mineral resource potential of large tracts of land. In other cases, new reconnaissance methods can be developed from methods usually used in detailed exploration. In Saudi Arabia, detailed spectral induced polarization studies of small areas were used to develop a new reconnaissance method suitable to assess the mineral potential of a very long carbonaceous zone.

The audiomagnetotelluric method, originally developed for mineral and geothermal exploration, is useful and cost effective when it is used in a reconnaissance mode in mineral resource assessments. One example is an audiomagnetotelluric study in New Mexico, where areas of probable subsurface hydrothermal alteration suggest that surface geochemical anomalies have a significant depth extent.

Some types of airborne electromagnetic measurements can be made in conjunction with other airborne measurements at little extra cost. Airborne very low frequency measurements have been used for a variety of purposes, including location of anomalously thin glacial drift in northern Minnesota and delineation of conductive strata in possibly mineralized metavolcanic rocks in Vermont and New Hampshire.

INTRODUCTION

Mineral resource assessment carried out to provide information for land use planning and development of public policy is an important but difficult task. Geophysics, as applied in this kind of mineral resource assessment, is not a well recognized or mature subdiscipline. Because of the many connections and similarities, it is natural to compare the use of geophysics in resource assessment with its use in exploration. The role of geophysics in mineral exploration is changing but nevertheless relatively well understood. There is a large body of published information on mineral exploration geophysics and an enormous amount of information resident in the files and minds of exploration geophysicists and geologists. The effectiveness of mineral exploration geophysics has often been tested by the drill, and the resulting information has been fed back to improve techniques and strategies. In contrast, despite the fact that geophysics has been used explicitly in mineral resource assessment of public lands for roughly two decades, little has been written on optimizing methods and strategies, in part because there are few opportunities to test the effectiveness of geophysics in mineral resource assessment programs by drilling or other objective criteria. Lack of such feedback hampers efforts to improve techniques and strategy.

Mineral exploration programs are carried out on three distinctly different scales: (1) regional-scale exploration of large areas to define smaller areas that have high potential for mineralization, (2) district-scale exploration to define specific areas where detailed prospecting is warranted, and (3) deposit-scale investigations, which are usually directed toward defining drill targets. Mineral resource appraisal (MRA) programs carried out by the U.S. Geological Survey (USGS) are directed at identification of permissive or favorable areas for the occurrence of mineral deposits in order to assess the mineral resource potential of those areas. Generally, study areas are of a size appropriate to regional- or district-scale exploration. Location of drill targets is not an objective of MRA programs, although detailed studies of known mineral deposits are sometimes appropriate, because they can improve insight into factors that are important in regional-scale studies. Mineral exploration programs and MRA programs have many similarities at the regional scale and, in many cases, at the district scale. The principal difference is that studies carried out by a government agency, such as the USGS, can consider more types of possible mineral resources than more narrowly focused commercial studies can. Consequently, geophysics should be applied more broadly in an MRA program than in an exploration program.

Time and funding for MRA programs are generally very limited in comparison with the resources available in exploration programs at the district scale or smaller, yet reliable quantitative estimates of resource potential are needed. Thus, it is important to select the optimum method or combination of geophysical methods for a particular program. The methods first used in MRA programs by the USGS were aeromagnetics and gravity, which, together with remote sensing, remain the primary methods. Increasing use is being made of geoelectrical methods to supplement or partially replace other methods. Geoelectrical methods respond to a set of rock properties different than that to which other methods respond. The most important of these properties are electrical resistivity and electrical polarization, which are governed by factors such as the quantity and mode of distribution of water and certain clay and metallic minerals within the rock. To some extent, these factors govern rock magnetization and density, as sensed by the magnetic and gravity methods, but electrical properties generally are not closely correlated with other geophysical parameters. Thus, geoelectrical methods are often useful in mapping geologic features that are not detectable by other methods (the converse is also true, of course). Also, because the depth of investigation of geoelectrical methods can be controlled, they are much more suitable than gravity and magnetic methods for mapping changes in rock properties with depth. Geoelectrical methods tend to be more expensive than gravity, magnetic, and remote sensing methods, and their higher costs generally preclude detailed geoelectrical studies of large areas. However, a number of geoelectrical methods can be used successfully in reconnaissance studies of large areas other geoelectrical methods are not suitable for deployment in a reconnaissance mode but are sometimes used for detailed studies of small areas when the results can be extrapolated to larger areas. There is a need to develop new geoelectrical techniques and new approaches for their use in MRA programs. The following examples illustrate preliminary USGS efforts in these directions.

The most commonly used geoelectrical methods in mineral exploration are airborne and ground-controlled source electromagnetic (EM) and induced polarization (IP) methods. In USGS MRA programs, it is seldom appropriate, from the standpoint of either objectives or costs, to make detailed surveys of large areas by these methods. However, reconnaissance surveys using these exploration methods are sometimes made as part of resource assessment studies.

One example is the use of airborne EM in MRA projects in the upper peninsula of Michigan (Heran and Smith, 1980; Geoterrex, 1981, 1982). The areas shown in figure 1 were flown for different MRA programs having different objectives. The long, narrow zone in the north-central part of the area (areas 1 and 2, fig. 1) area was flown to identify the pinchout contact between basement crystalline rocks and the Middle Proterozoic Jacobsville Sandstone. A small survey (area 3, fig. 1) was flown to test the electrical nature of a suspected cryptovolcanic structure. Another small survey (area 4, fig. 1) was flown to map a gneiss dome complex. These surveys were flown at a flight-line spacing of 1/4 mi instead of the more common 1/8-mi spacing used in mineral exploration programs. Surveys were flown at 1/2-mi line spacing in the area in the southeastern part of the quadrangle (area 5, fig. 1) to help provide a better geologic map of a gneiss dome complex that has several different types of potential mineralization and in the small area in the west (area 6, fig. 1) to test whether permissive areas for mineralization occur within a wilderness study area.

The Middle Proterozoic Jacobsville Sandstone uncomformably overlies Early Proterozoic and Archean rocks of varying lithology. At the time that the survey was made, this area was thought to be analogous to the Athabasca Basin of Canada, which hosts several world-class uranium and base-metal deposits. A portion of the Jacobsville survey is shown in figure 2. The locations of conductive zones along the flight lines are indicated by solid lines. The airborne survey demonstrated that, near its pinchout contact with older rocks, the Jacobsville is much more conductive than the generally equivalent Athabasca Sandstone in Canada. A few dc resistivity soundings showed that the conductive units in the Jacobsville are caused by intercalated mudstones. The pervasive occurrence of these mudstones, as indicated by the airborne EM survey, was a major factor in the abandonment of the hypothesis that the Jacobsville Basin is lithologically similar to the Athabasca Basin. The contact of the Jacobsville with the older rocks is delineated by the termination of conductors in the sandstone; the contact extends all the way across the upper part of the area shown in figure 2.

Two other conductive zones are shown in figure 2; the short one is probably a conductive graphitic zone, but it is characteristic of anomalies caused by massive sulfides. The long, narrow zone is probably caused by graphite along a shear zone. Combined interpretation of the EM and magnetic maps of the same area suggests an offset of about 2 to 3 km along the zone. The inferred graphitic shear zone could represent a plumbing system and a reducing environment favorable for the occurrence of uranium deposits.

The airborne EM survey of the gneiss dome complexes (areas 4 and 5, fig. 1) showed several very long conductive bands and a few short isolated conductors. Geophysical mapping of the long conductive bands, which are probably graphitic zones in metasedimentary rocks, improved the geologic map of the area by adding new stratigraphic control and a better knowledge of the lithology. Some of the short anomalies are typical of those observed over massive sulfide deposits, and their presence indicates a higher potential for massive sulfide deposits in the area than the inferred lithology had indicated. From an estimate of the number of anomalies that would have been found by a detailed survey and from available statistics on the probability that a favorable airborne EM anomaly in this kind of environment is a mineral deposit, a

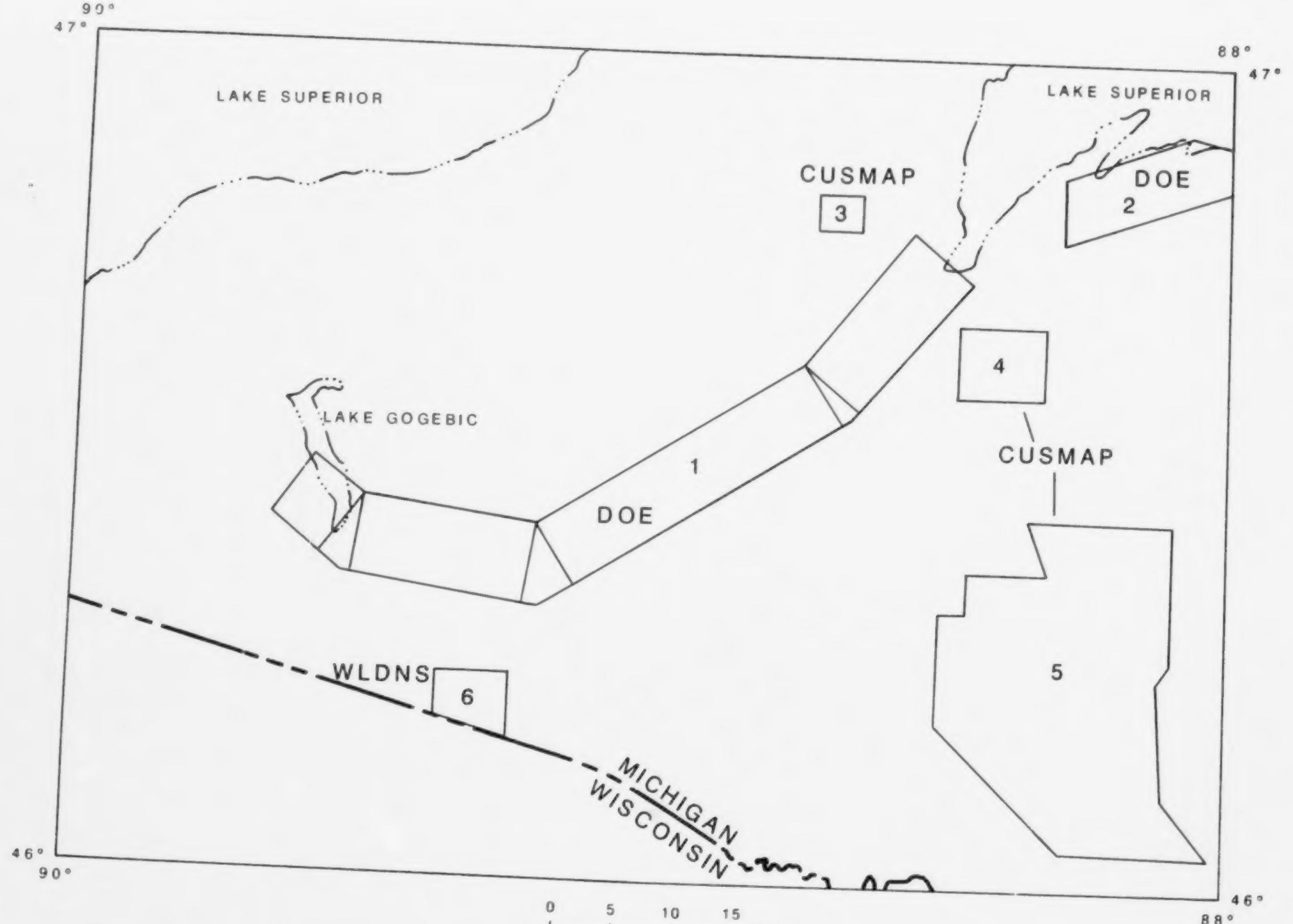
90°
47°
88°
47°
LAKE SUPERIOR
LAKE SUPERIOR
CUSMAP
3
DOE
2
4
CUSMAP
LAKE GOGEBIC
1
DOE
5
WLDNS
6
MICHIGAN
WISCONSIN
46°
90°
46°
88°
0
5
10
15
miles

FIGURE 1.—Index map showing locations of airborne EM surveys within the Iron River 1:250,000 quadrangle of Michigan. Areas 3, 4, and 5 were flown as part of the Iron River CUSMAP program. Areas 1 and 2 were part of a study of permissive areas for world-class uranium deposits funded by the National Uranium Resource Evaluation program sponsored by the U.S. Department of Energy. Area 6 comprises a wilderness study area.

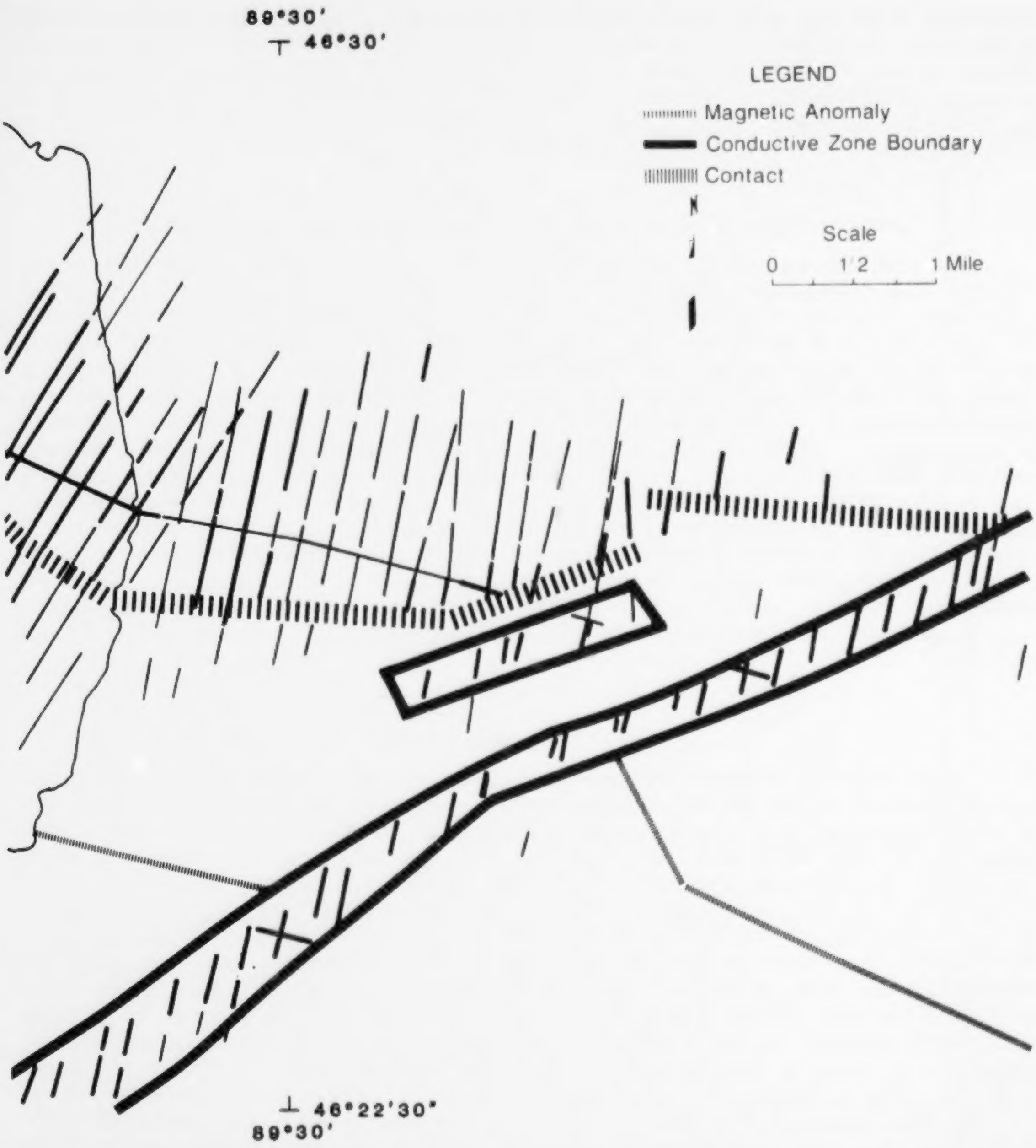
89°30'
46°30'
LEGEND
Magnetic Anomaly
Conductive Zone Boundary
Contact
Scale
0
1/2
1 Mile
46°22'30"
89°30'

FIGURE 2.--Airborne EM results for the easternmost part of area 1 (fig. 1). Heavy lines are strong electrical anomalies, and lighter lines are moderate anomalies.

quantitative estimate of the resource potential for massive sulfide deposits could be made.

In the above examples, airborne EM surveys have helped to formulate hypotheses concerning potentially mineralized areas and have also served as an airborne geologic mapping tool. However, the hypotheses about mineral resources have not, at this time, been tested. After the airborne EM surveys over the Jacobsville contact were completed, a number of companies conducted exploration programs that included drilling in the area. There have been no announced discoveries of mineral deposits; whether this silence is due to an actual lack of mineral deposits or to a changing political and economic environment is unknown. The lack of feedback in the mineral resource appraisals in this specific area is a good example of the difficulties that the USGS has in evaluating the effectiveness of MRA methods.

APPLICATION OF AIRBORNE VERY LOW FREQUENCY METHODS

In most cases, controlled-source airborne EM methods are too expensive to use in resource assessment, even at 1/2-mi line spacing. However, aeromagnetic surveys are generally conducted, so the question naturally arises as to whether there are inexpensive EM techniques that use light-weight equipment and can be deployed in a light aircraft along with a magnetometer. The airborne very low frequency (VLF) technique meets these requirements. The equipment consists of a lightweight receiver that measures several components of the signals from VLF radio communication transmitters operating at frequencies of 20 to 25 kHz. Ground VLF methods are frequently used in mineral exploration in favorable terranes where overburden is thin or not conductive. Airborne VLF is occasionally used to supplement other EM and magnetic techniques in mineral exploration, but the method is generally ineffective as a primary tool. Airborne VLF tends to respond to minor conductive features that cannot be distinguished from possible mineral deposits, and conductive overburden or rugged topography further limits its usefulness. However, the method can be very useful in mapping conductors in crystalline rock in areas where the overburden is thin or nonconductive and the terrain is not extreme.

Glens Falls CUSMAP Study

Half of the Glens Falls 1:250,000-scale quadrangle in Vermont and New Hampshire was surveyed at 1/2-mi spacing by using airborne magnetics and VLF EM (fig. 3) as part of a Conterminous U. S. Mineral Appraisal Program (CUSMAP) project. Preliminary inspection of the data and field checking indicate that the data delineate many conductive carbonaceous, graphitic, or sulfidic zones. The system used by the USGS measures inphase (or real) (R) and quadrature (or imaginary) (Q) parts of three orthogonal spatial components of the VLF magnetic field and the quadrature part of the horizontal electrical field. Profiles of five channels of VLF information and the magnetic information have been plotted for a short section of lines 136 and 137 (figs. 4, 5). A major conductor between 72°35' and 72°36' on lines 136 and 137 is marked by a large asymmetric anomaly in the vertical VLF magnetic field (HVR and HVQ) and a more symmetric anomaly in the horizontal VLF magnetic field (HIR and HIQ) in the flight direction. The horizontal field anomaly peaks near the midpoint or "crossover" of the vertical field anomaly. The anomaly in the VLF magnetic field is also marked by a less distinctive low in the VLF electrical field (EHQ). The generally similar shapes of the VLF profiles on the two lines indicate continuity in the electrical characteristics along strike between the two lines. This point is better illustrated by profiles of HVR for several lines (fig. 6). Obviously, the major conductor is continuous over a distance of at least 2.5 mi, and its strike is north-northeast. A small magnetic anomaly coincides approximately with the conductor, but its position relative to the conductor changes somewhat from line to line, as figures 4 and 5 show. A ground VLF traverse was run over a portion of line 136 extending eastward from the anomaly (fig. 7). The tilt angle is roughly equivalent to HVR. The ground profile shows many more minor features than the airborne profile, but, overall, it shows large a asymmetric anomaly that coincides in position with the main airborne anomaly. Detailed geologic mapping is not yet available

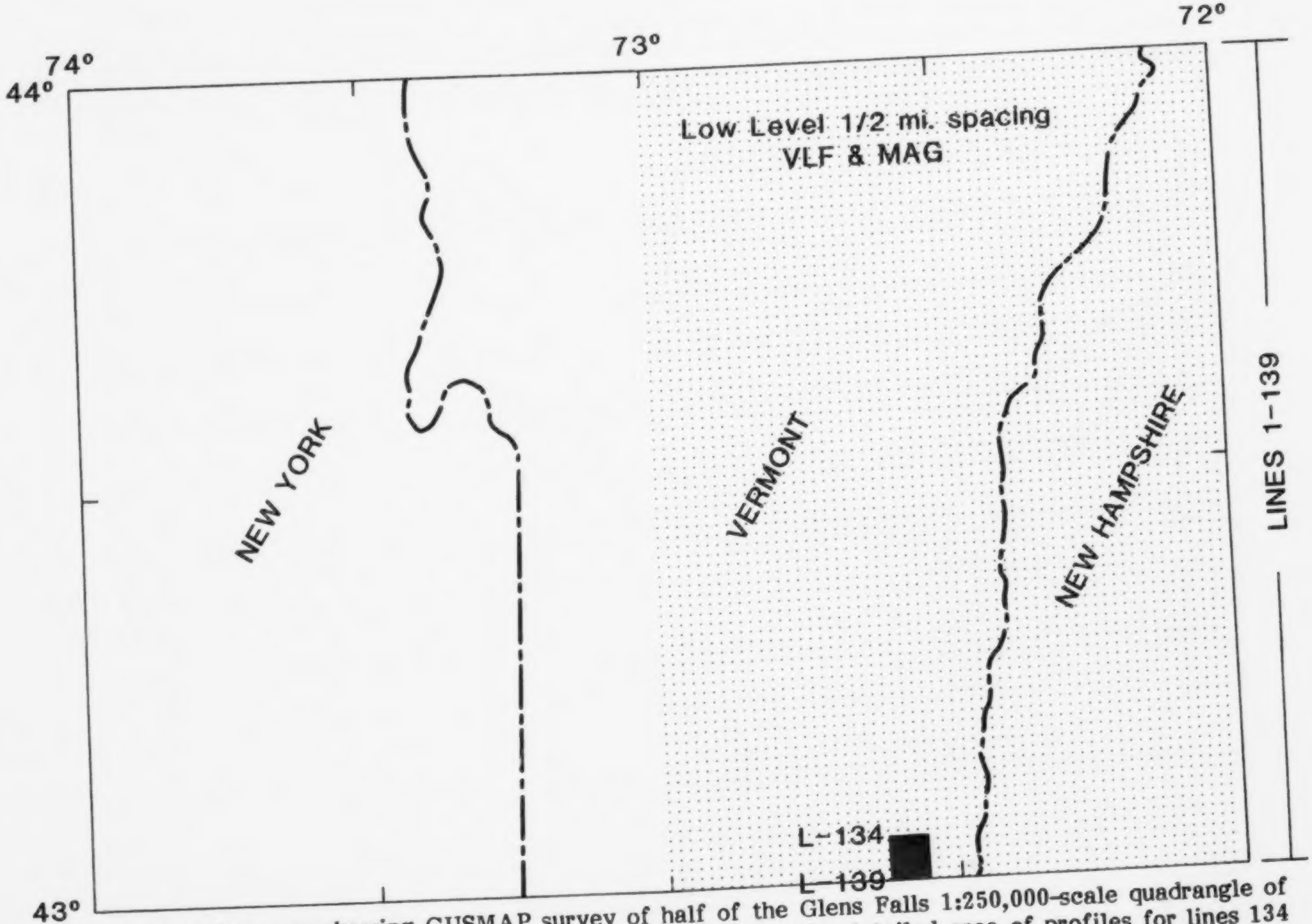
74°
44°
73°
72°
43°
Low Level 1/2 mi. spacing
VLF & MAG
NEW YORK
VERMONT
NEW HAMPSHIRE
LINES 1-139
L-134
L-139

FIGURE 3.—Index map showing CUSMAP survey of half of the Glens Falls 1:250,000-scale quadrangle of Vermont and New Hampshire. The solid square indicates the detailed area of profiles for lines 134 through 139 (figs. 4-7).

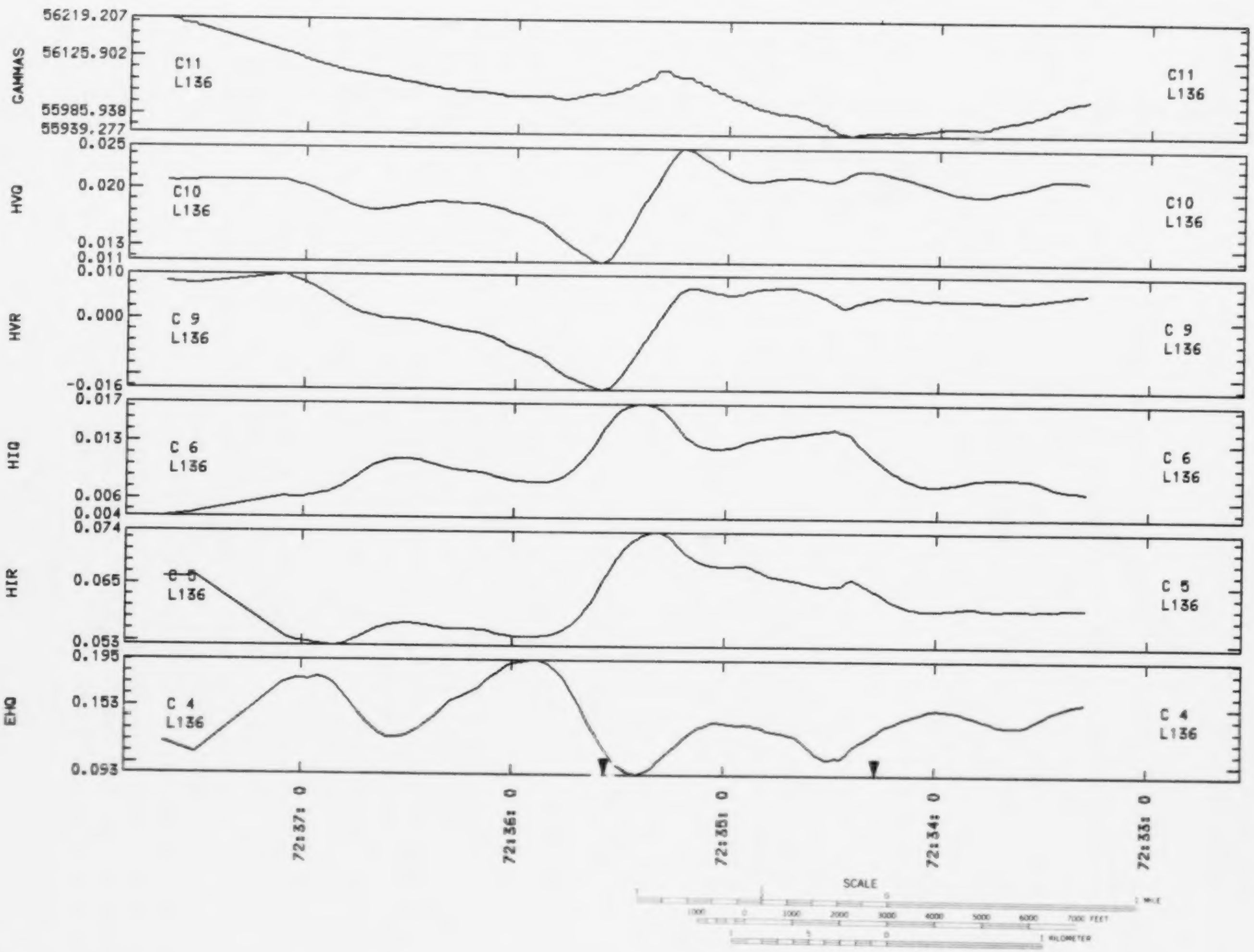

FIGURE 4.—Airborne profiles of vertical (HVR, HVQ) and horizontal (HIR, HIQ) VLF magnetic fields, horizontal VLF electric field (EHQ), and the intensity of Earth's magnetic field for part of line 136. Solid triangles indicate the extent of the ground traverse. Profiles are from the detailed area of the Glens Falls CUSMAP survey (fig. 3).

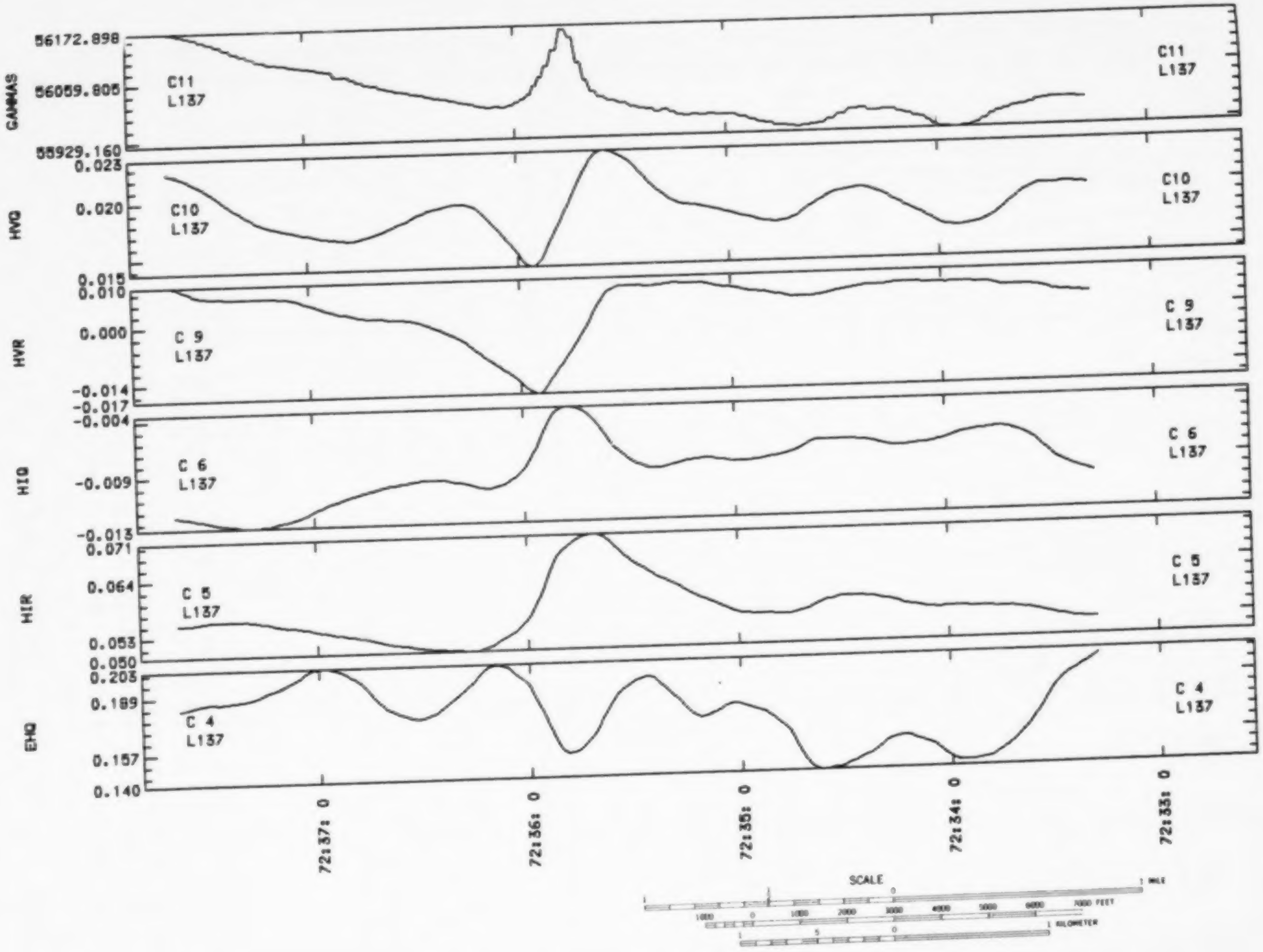

FIGURE 5.—Airborne profiles of vertical (HVR, HVQ) and horizontal (HIR, HIQ) VLF magnetic fields, horizontal VLF electric field (EHQ), and the intensity of Earth's magnetic field for part of line 137 of the Glens Falls CUSMAP survey (fig. 3).

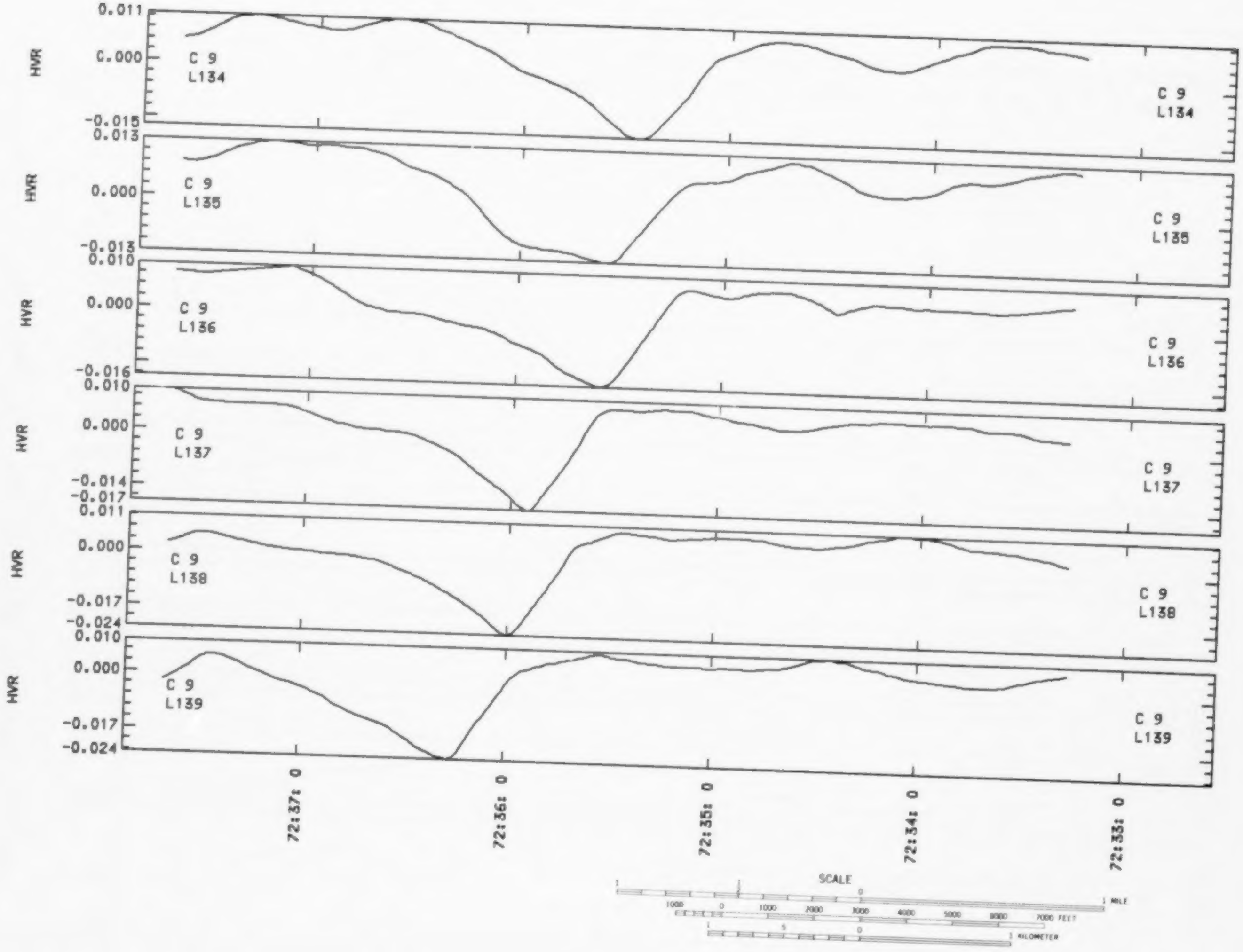

FIGURE 6.—Airborne profiles of vertical VLF magnetic field for part of lines 134 through 139 of the Glens Falls CUSMAP survey (fig. 3).

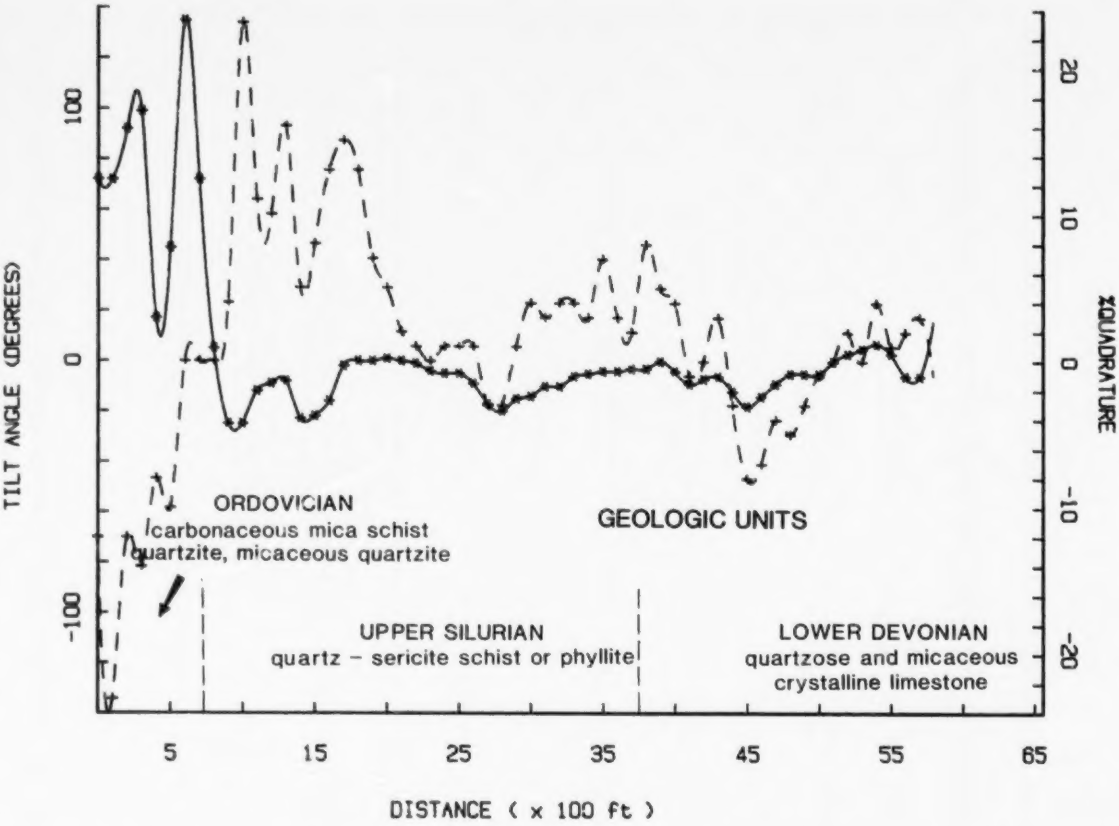

FIGURE 7.--Ground VLF profiles of tilt angle (crosses) and quadrature or ellipticity (asterisks) for part of line 136. See figure 4 for location of ground traverse.

for this area, but the State map (Doll and others, 1961) indicates that carbonaceous mica schists occur near the crossover point in the anomaly. VLF results such as these will add new structural and lithologic information to the geologic map that is being produced as part of the CUSMAP project. Some of the conductors traced by airborne VLF may be indicators of permissive or favorable ground for the occurrence of mineral deposits.

Northern Minnesota CUSMAP Study

Combined airborne magnetic and VLF surveys are being conducted as part of a CUSMAP study in northern Minnesota. Glacial deposits are much more extensive in this area than they are in the Glens Falls quadrangle; thus, geologic mapping is extremely difficult owing to the paucity of outcrops. Conductive lake deposits in the glacial drift prevent VLF mapping of bedrock conductors over most of the area. However, the VLF data appear to have one very practical use--delineation of localities favorable for shallow drilling or surface geologic mapping where glacial deposits are thin or absent. To illustrate this application, results for a small area southwest of International Falls, Minn., are shown in figures 8, 9, and 10. The quadrature electrical field was expressed in the form of apparent resistivity and plotted as profiles by using a linear scale (fig. 8) and a logarithmic scale (fig. 9). The calculated values of apparent resistivity are correct only where the Earth is homogenous, but the results are still useful in qualitative interpretation. Plotting the data on two different scales aids the interpreter in

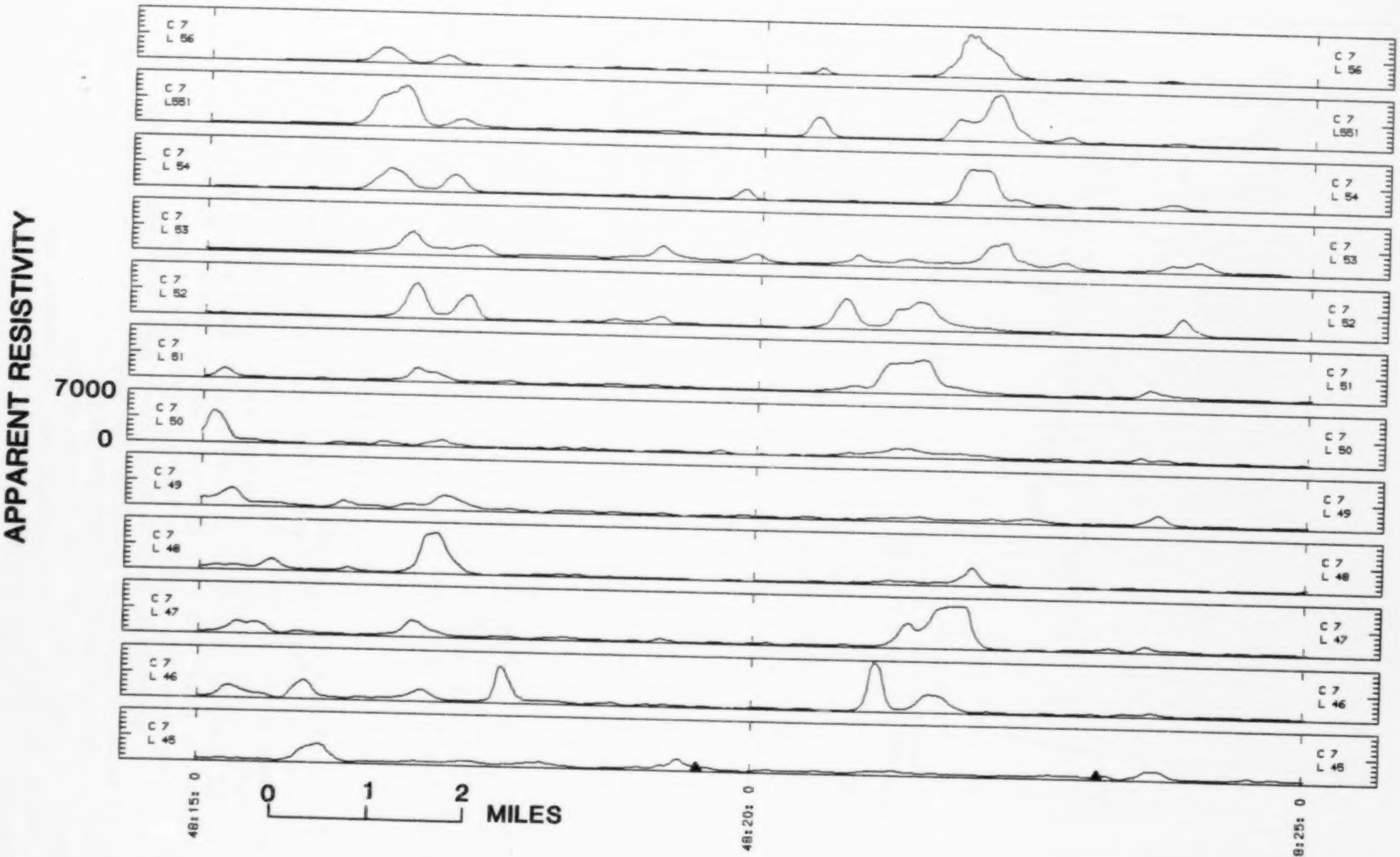

FIGURE 8.—Airborne VLF apparent resistivities (in ohm meters) for part of 12 lines in northern Minnesota plotted on a linear scale.

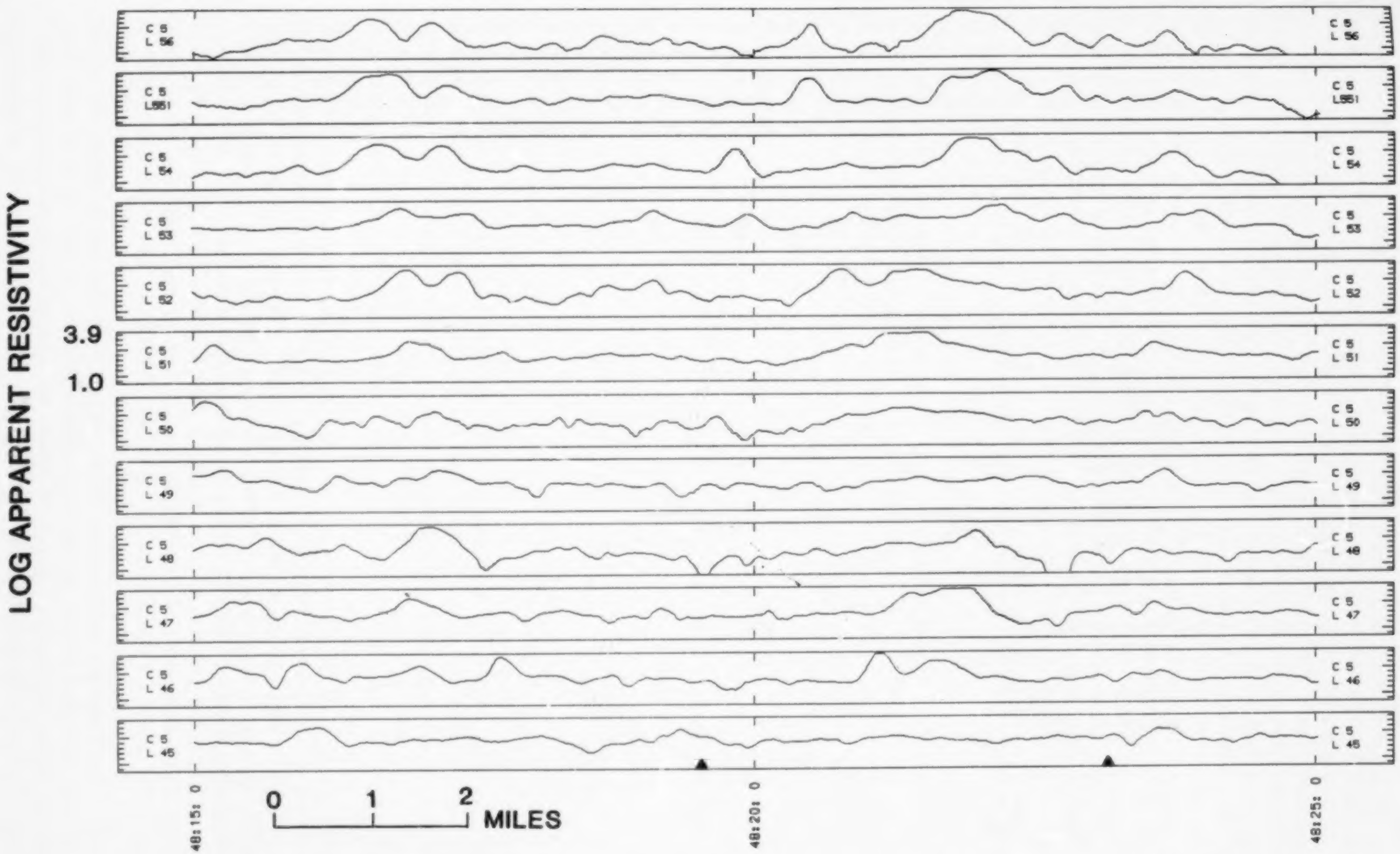

FIGURE 9.—Airborne VLF apparent resistivities for part of 12 lines in northern Minnesota plotted on a logarithmic scale.

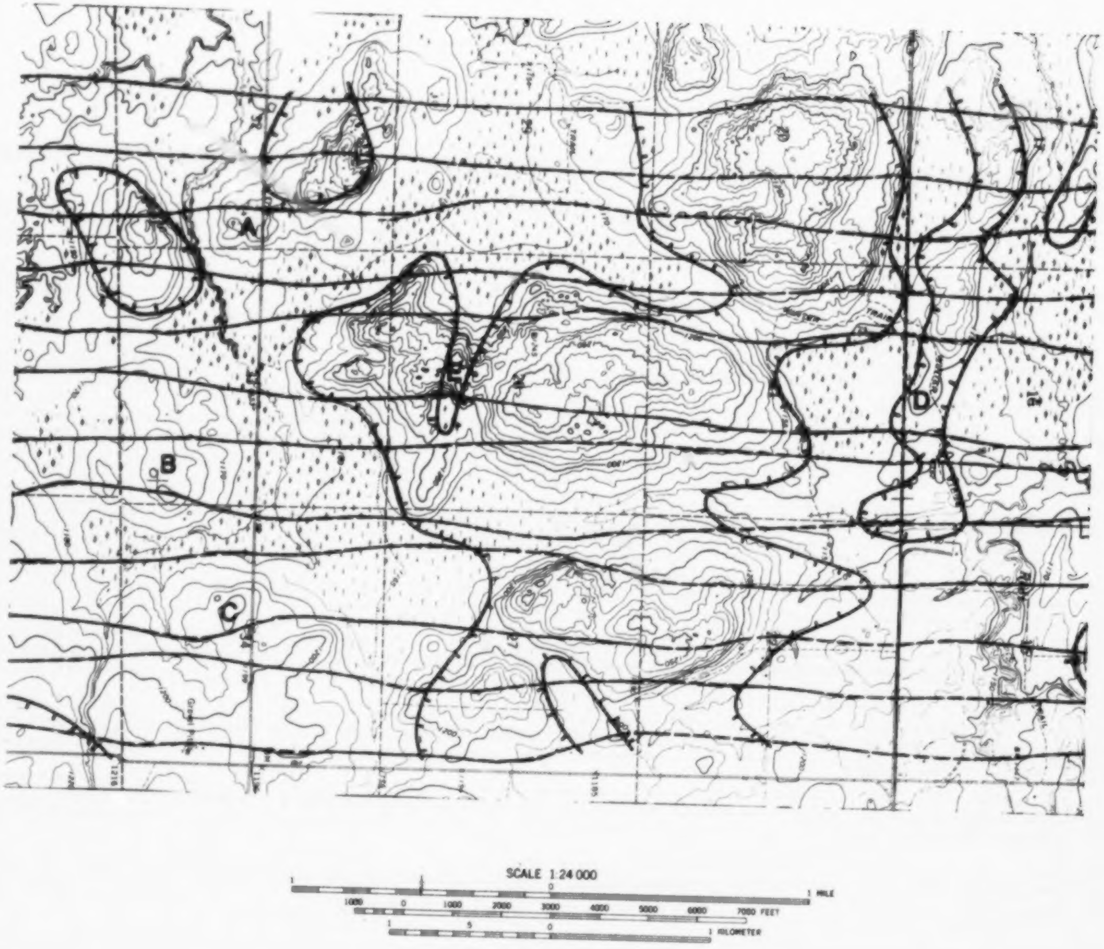
A
B
C
D
E
SCALE 1:24 000
1 MILE
7000 FEET
1 KILOMETER

FIGURE 10.—Flight lines (dashed) and areas of high resistivity (hachured) superimposed on the topographic map of the area southwest of International Falls, Minn. Areas labeled A, B, and C are topographically high but do not have high resistivities. The area labeled D is topographically low but has a high resistivity. The feature labeled E could be caused by a narrow valley in the bedrock or by conductive bedrock.

separating two classes of features. From figure 8, it is apparent that there are localities where the resistivity is very much higher than the general background level. These high resistivities are believed to mark areas of outcrop or very shallow drift. Between the areas of very high resistivity, the resistivity is variable (fig. 9) but generally quite low; in many localities, it is less than 100 Ωm. An outline of areas where resistivity is highest is shown on the topographic map of part of the area, along with the locations of the flight lines (fig. 10). Generally, the areas having high resistivity coincide with topographically high areas. If the correlation were perfect the VLF results would add little useful information. However there are a number of topographically high areas (A, B, and C on fig. 10) where the resistivity is not high, and there are topographically low areas (D, fig. 10) where the resistivity is substantially higher than that in the surrounding areas. The feature marked E (fig. 10) could be caused by a narrow valley in the bedrock or by conductive bedrock. Thus, the VLF data provide information that is not available on the topographic map. Examination of field data shows that, farther west in the project area, isolated localities having high resistivity are surrounded by large areas of monotonously low resistivity. These localities of high resistivity do not necessarily coincide with topographic highs, and it is believed that many of them mark bedrock ridges that cannot be identified from topographic maps, although they could represent sand and gravel deposits. The discovery of previously unknown outcrops or near-surface basement will be beneficial to geologic mapping in much of the area.

In these two examples of the use of airborne VLF, the primary objective has been to contribute to the geologic map. When the project has been completed, it should be possible to accurately evaluate of the usefulness of the simple application of the method in northern Minnesota but perhaps not that of the more complex application in Vermont and New Hampshire.

APPLICATION OF INDUCED POLARIZATION METHODS

Geoelectrical exploration for massive sulfide deposits within metasedimentary sequences has been a challenge for more than three decades (Patterson, 1970). Conductive carbonaceous or graphitic zones in metasedimentary rocks can have strike lengths of up to several tens of kilometers. Economic massive sulfides having about the same electrical response can occur within or in proximity to such zones. Advanced induced polarization (IP) methods, which measure over a broad frequency range the ability of rocks to store electrical charge (spectral induced polarization or SIP), have been applied to the discrimination of conductive graphites and sulfides (Pelton and others, 1980). Laboratory measurements show that, at low frequencies, the response of massive sulfides can increase with frequency, whereas the response of carbonaceous rocks decreases in the same frequency range (fig. 11). Published field results also show that, in general, graphitic rocks and massive sulfides produce different-shaped IP response curves or spectra, as figure 11 shows. These data led to testing a new concept for regional IP mineral assessment in the Kingdom of Saudi Arabia, where conductive carbonaceous zones occur in a Proterozoic greenstone belt in the Wadi Bidah district. A prominent zone was traced for over 50 km by airborne EM and other surveys (Smith and others, 1983b). The zone of metasedimentary rocks hosts a number of massive sulfide deposits that were mined in ancient times and drilled in more recent times. The detailed MRA program in the Wadi Bidah district used standard geologic, geochemical, and geophysical methods (Smith and others, 1983b). The work was done largely in areas of exposed gossans and included drilling of permissive areas for massive sulfide mineralization. The drilling results, which were made available to the USGS, defined scattered massive copper deposits of only a few million tons in total. Although standard MRA methods proved to be technically successful, the hypothesis that there are larger massive sulfide deposits having no surficial gossan expression remained untested. Thus, the question of applying new reconnaissance MRA methods remained open. One of the methods considered was to apply the SIP technique to discriminate massive sulfides and carbonaceous rocks.

Test surveys were carried out at the Rabathan massive sulfide deposit to determine whether different-shaped IP response curves would be detected in field surveys. Previous electrical geophysical surveys had shown that both massive sulfides and carbonaceous rocks have low resistivities and moderate IP responses. Laboratory measurements of drill-core samples from the district were encouraging, because there appeared to be differences in the shapes of the IP responses from carbonaceous and massive sulfide samples (Smith and others, 1983a).

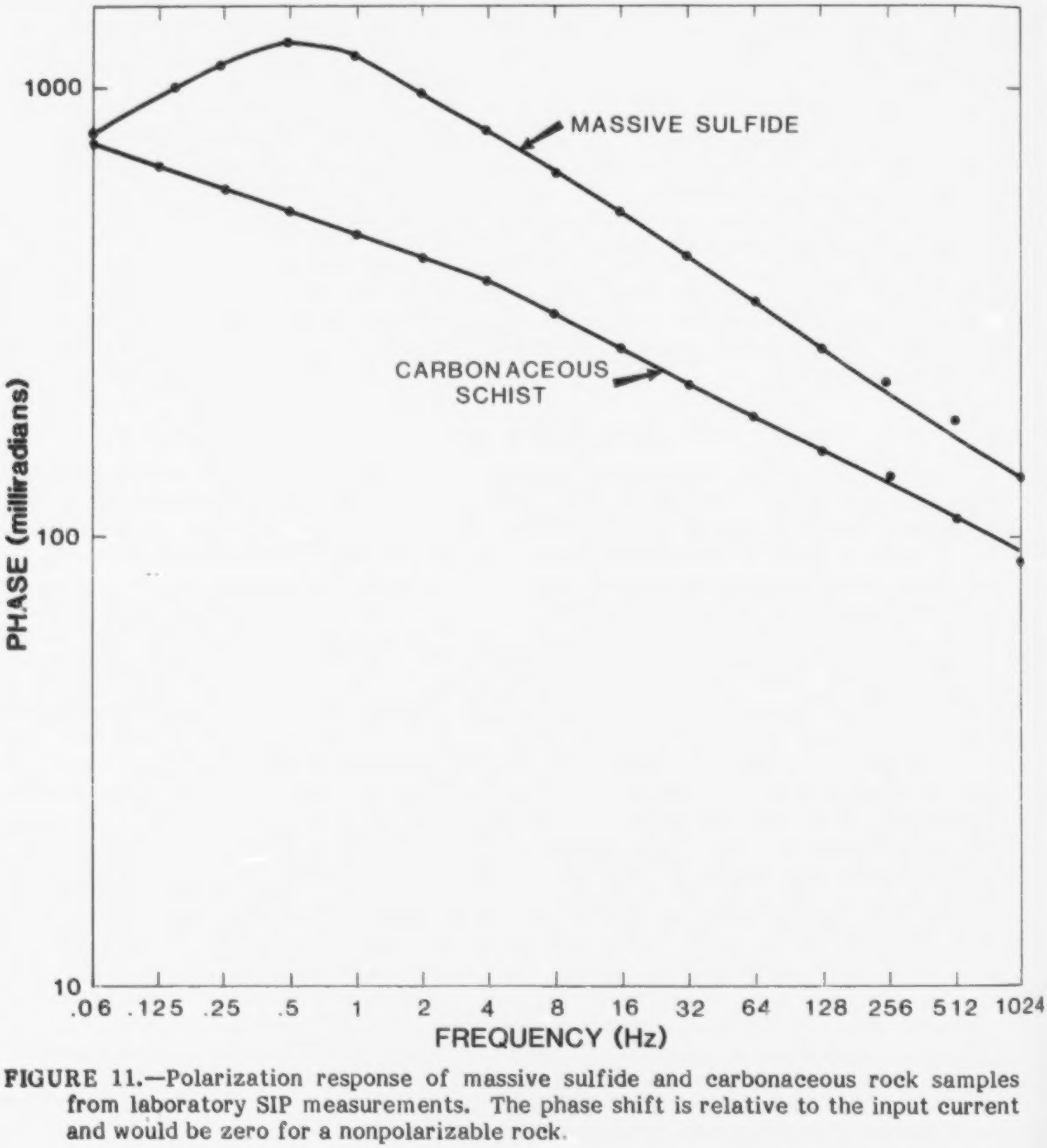

FIGURE 11.—Polarization response of massive sulfide and carbonaceous rock samples from laboratory SIP measurements. The phase shift is relative to the input current and would be zero for a nonpolarizable rock.

SIP measurements using a 50-m dipole-dipole array were carried out on two lines at the Rabathan deposit. The interpretation scheme for spectral shape was based on whether the curves increased or decreased as frequency was varied from 0.06 to 1 Hz. Figure 11 indicates that massive sulfides should be represented by increasing spectra and that carbonaceous rocks should be represented by decreasing spectra over this frequency range. Results from the survey across the known massive sulfide zone are shown in figure 12. The pseudosection shown here was created by plotting the field measurements at the intersection of 45° lines drawn from the center of the transmitter and receiver dipoles. The shaded central area of figure 12 represents field measurements having an increasing phase spectrum, which correlates well with the known massive sulfide mineralization. The adjacent carbonaceous rocks are associated with decreasing phase spectra. SIP measurements along a line south of the mineralization, over only carbonaceous conductors, yielded no increasing spectral shapes.

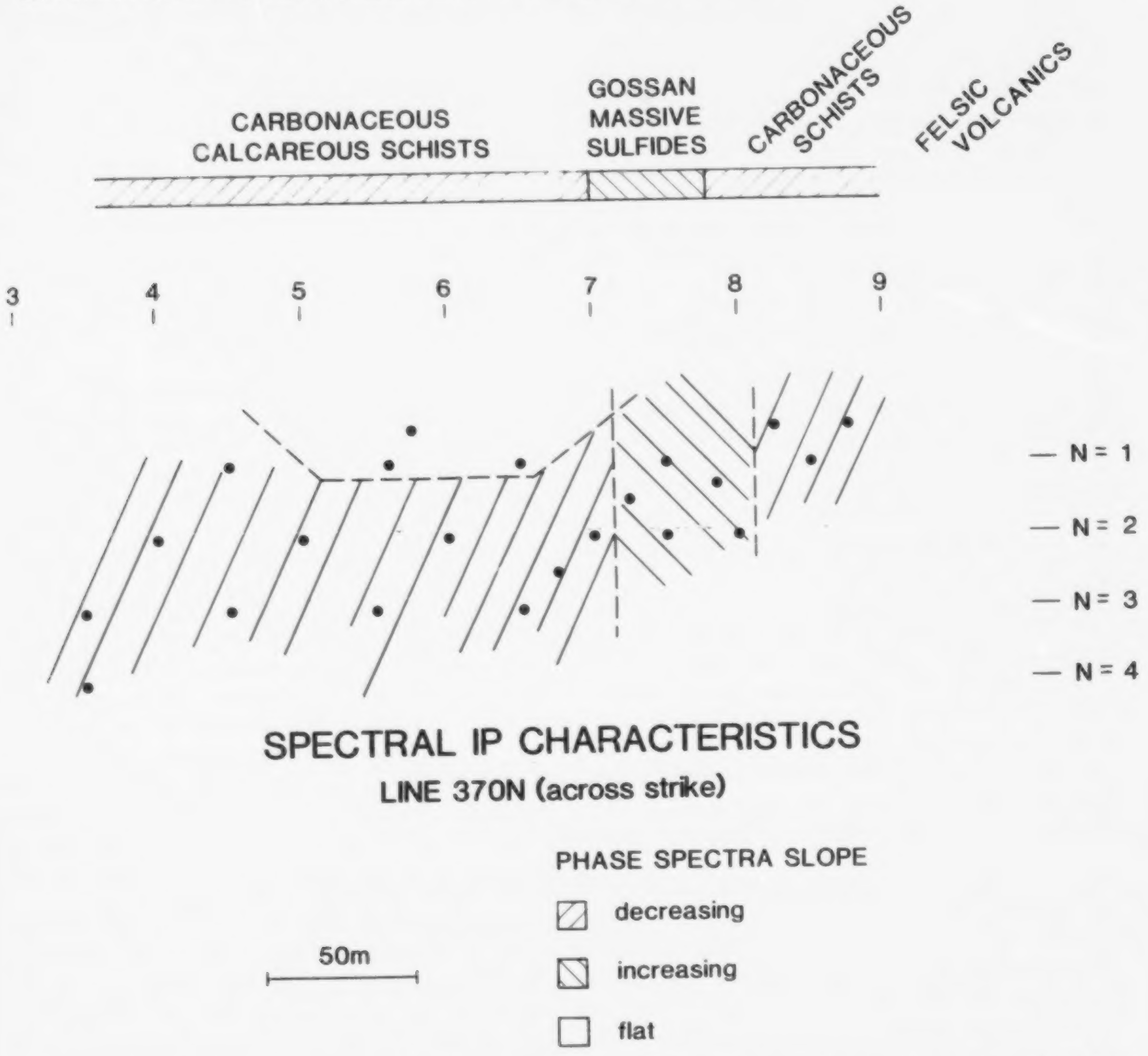
CARBONACEOUS CALCAREOUS SCHISTS
GOSSAN MASSIVE SULFIDES
CARBONACEOUS SCHISTS
FELSIC VOLCANICS
3
4
5
6
7
8
9
— N = 1
— N = 2
— N = 3
— N = 4
SPECTRAL IP CHARACTERISTICS
LINE 370N (across strike)
PHASE SPECTRA SLOPE
▨ decreasing
▧ increasing
☐ flat
50m

FIGURE 12.--Interpretation of SIP phase spectra shown in pseudosection form. The slope of the phase spectra is determined from measurements below 2 Hz. The east-west profile is across the strike of a known massive sulfide deposit.

Although the method appears to work, it would not be a reconnaissance technique if lines were run across strike, as they are in the usual exploration mode. To avoid missing possibly significant deposits, SIP lines on the order of 1 km long would have to be placed across strike at intervals of 150 m along the entire length of the 50-km zone. As an alternative to this standard approach, the possibility of surveying down the strike of the known conductive zone was tested. The results (fig. 13) show that the discrimination between carbonaceous and massive sulfide-bearing rocks achieved by surveying across strike can also be obtained by surveying along strike, a technique that results in large savings in time and cost. This exercise shows how a detailed prospecting technique can be used in a reconnaissance mode.

The substantial differences between the IP spectra of massive sulfides and those of graphites illustrated above suggest that there may be other potential applications of

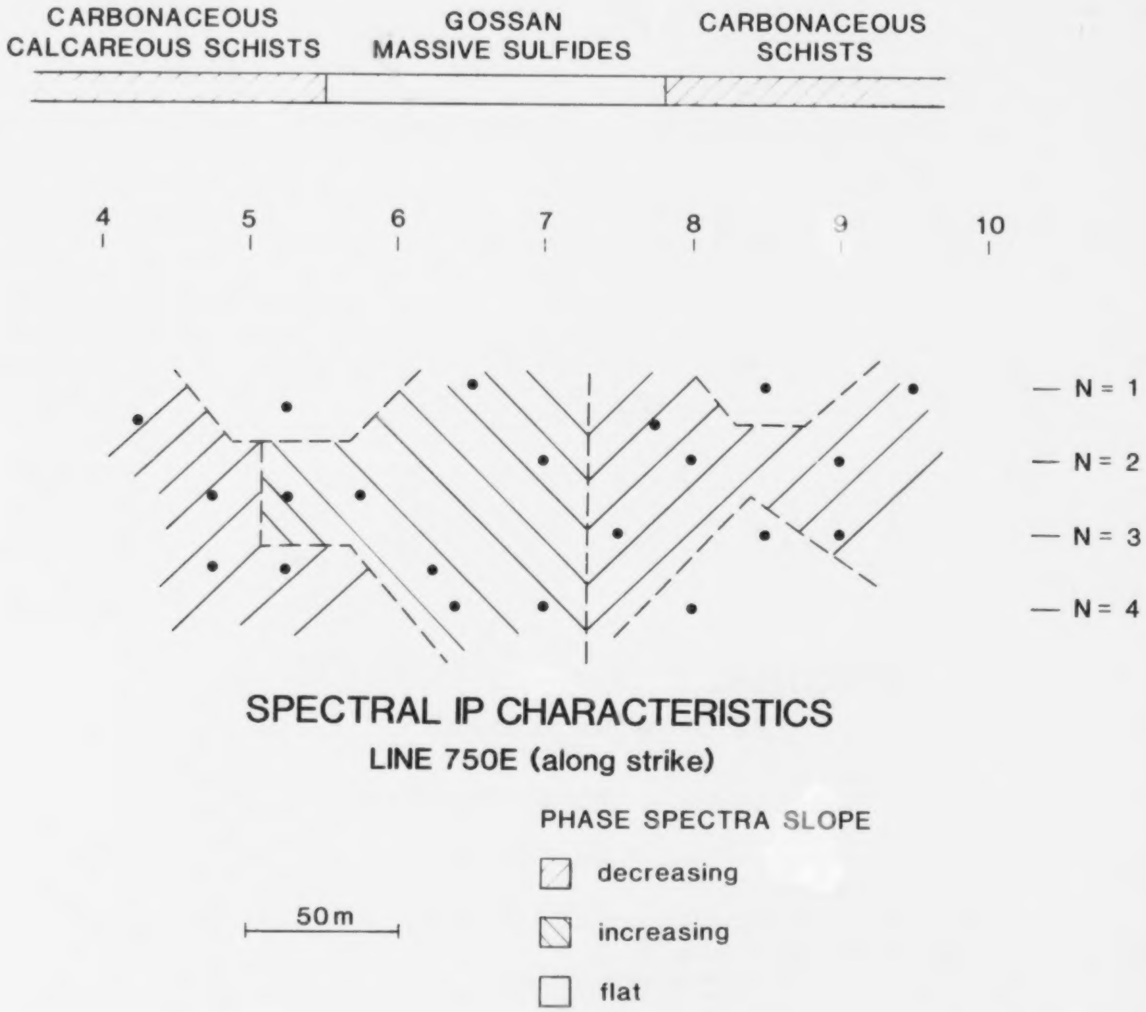
CARBONACEOUS CALCAREOUS SCHISTS
GOSSAN MASSIVE SULFIDES
CARBONACEOUS SCHISTS
4
5
6
7
8
9
10
N = 1
N = 2
N = 3
N = 4
SPECTRAL IP CHARACTERISTICS
LINE 750E (along strike)
PHASE SPECTRA SLOPE
decreasing
increasing
flat
50 m

FIGURE 13.—SIP phase spectra slopes plotted like those in figure 12. The north-south profile is along the strike of the same massive sulfide shown in figure 12.

SIP in MRA studies that have not yet been fully exploited. High temperatures, which transform carbonaceous ooze to graphite (maturation or graphitization), cause a large irreversible decrease in the electrical resistivity, as figure 14 shows. Corresponding changes in polarization properties are not as well studied, but they can be equally important. Maturation of organic material accompanies the processes that create hydrocarbon and metallic mineral deposits. Consequently, electrical methods might be used to map degree of maturation, which, in turn, is an indicator of mineralization processes and hydrocarbon generation.

One such application is suggested from a few detailed SIP measurements made in the Getchell district of north-central Nevada (Heran and Smith, 1984). This area is currently of interest to explorationists owing to recently discovered disseminated gold mineralization. The deposits are often associated with carbonaceous material that has apparently been transported from the surrounding host rocks. The exact temporal and spatial associations with gold mineralization are being debated and are under study by several groups of scientists. However, detailed in situ electrical measurements of rocks containing "altered" or transported carbonaceous material show that their SIP shape is distinctly different from that of the "fresh" host rocks containing carbonaceous material (fig. 15). Whether this difference is due to textural or maturation characteristics is being studied. These limited studies suggest the possibility that SIP methods might be used to detect areas favorable for gold mineralization through differences in spectral shape.

APPLICATION OF THE AUDIOMAGNETOTELLURIC METHOD

The audiomagnetotelluric (AMT) method is a high-frequency variant of the magnetotelluric (MT) method, which measures the ratio of electrical and magnetic fields of natural origin. In the AMT method, measurements are made at a number of frequencies extending from several hertz to about 20 kHz. The depth of investigation depends on both the frequencies and the resistivities of the rocks; thus, the method inherently provides more information on variations in lithology and structures with depth than gravity and magnetic methods or single-frequency EM profiling methods such as VLF do.

The AMT method was originally proposed as a means of exploring for particular types of conductive mineral deposits (Strangway and others, 1973). In its original form, however, the method was never used very extensively in prospecting. Recently, a variation of the method termed controlled-source audiomagnetotellurics, in which a local transmitter is used as a source of energy, has been popular for detailed exploration. The USGS first developed AMT techniques for assessing geothermal resources (Hoover and others, 1978). Generally, they were used with rather wide spacing between stations for reconnaissance purposes. For the past 7 or 8 years, the USGS has used the AMT method in variety of MRA investigations in the CUSMAP program, in the study of potential wilderness areas, and in resource assessment of Indian lands.

In northern New Mexico, AMT was used to map the resistivity structure of the Questa caldera and to map the outline of a mostly concealed batholith (Long, 1985). In addition, the AMT data delineated a number of low-resistivity areas that are likely caused by hydrothermal alteration. The lower part of the Middle Proterozoic Prichard Formation in the Belt Basin of Montana is highly conductive because it contains carbonaceous and sulfidic units. These conductive rocks serve as a marker horizon that can be mapped by AMT wherever it occurs within a few kilometers of the surface and could also serve as host rocks for massive sulfide deposits, such as those at Sullivan in British Columbia. Through his mapping the position of the lower Prichard, using regional AMT surveys, Long (1983) delineated faults and other structures in the area.

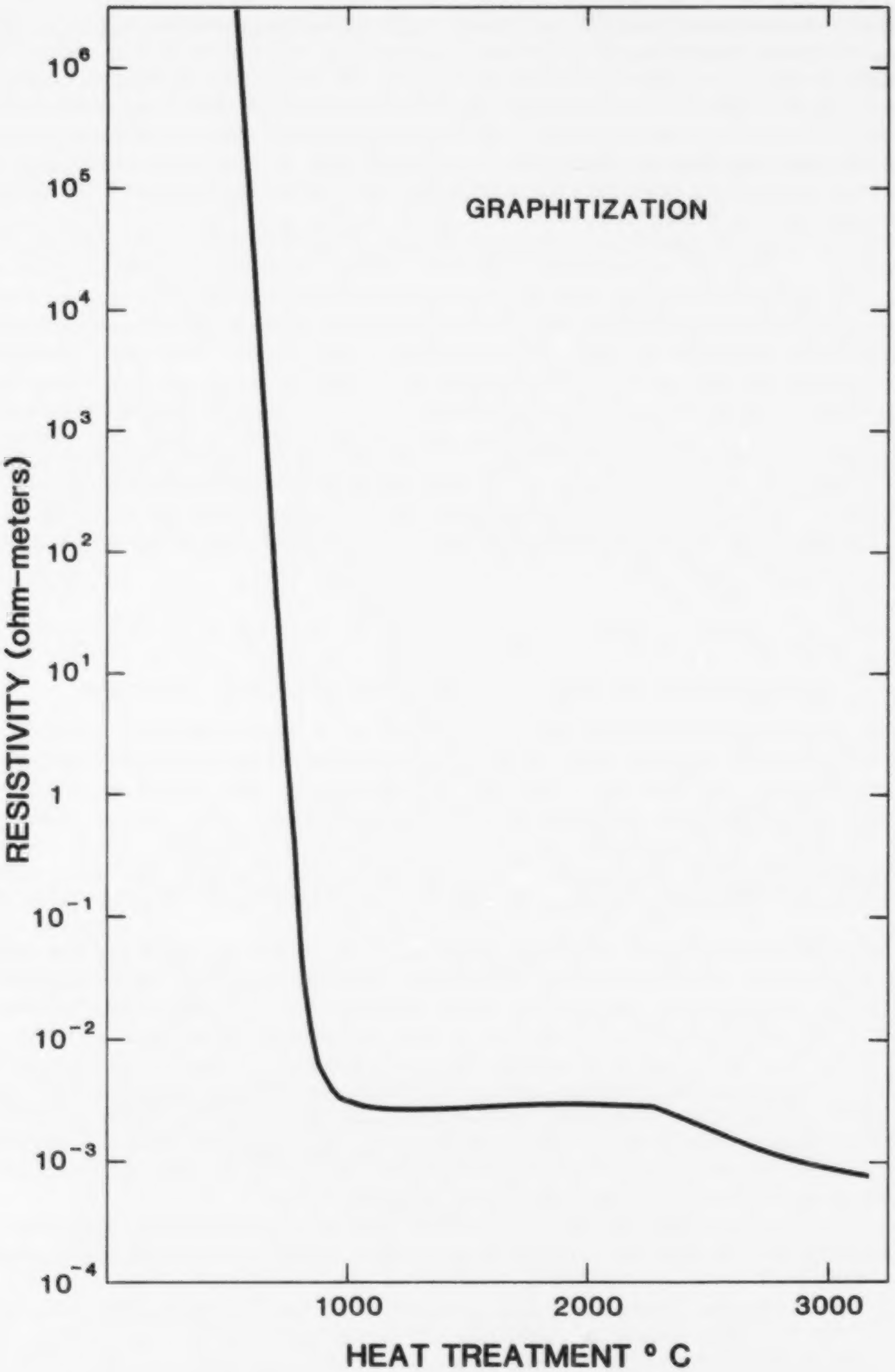

FIGURE 14.—Variation in resistivity of carbonaceous material as a function of heat treatment. The material has been heated to the temperature shown in the graph (at room pressure) and then allowed to cool to room temperature.

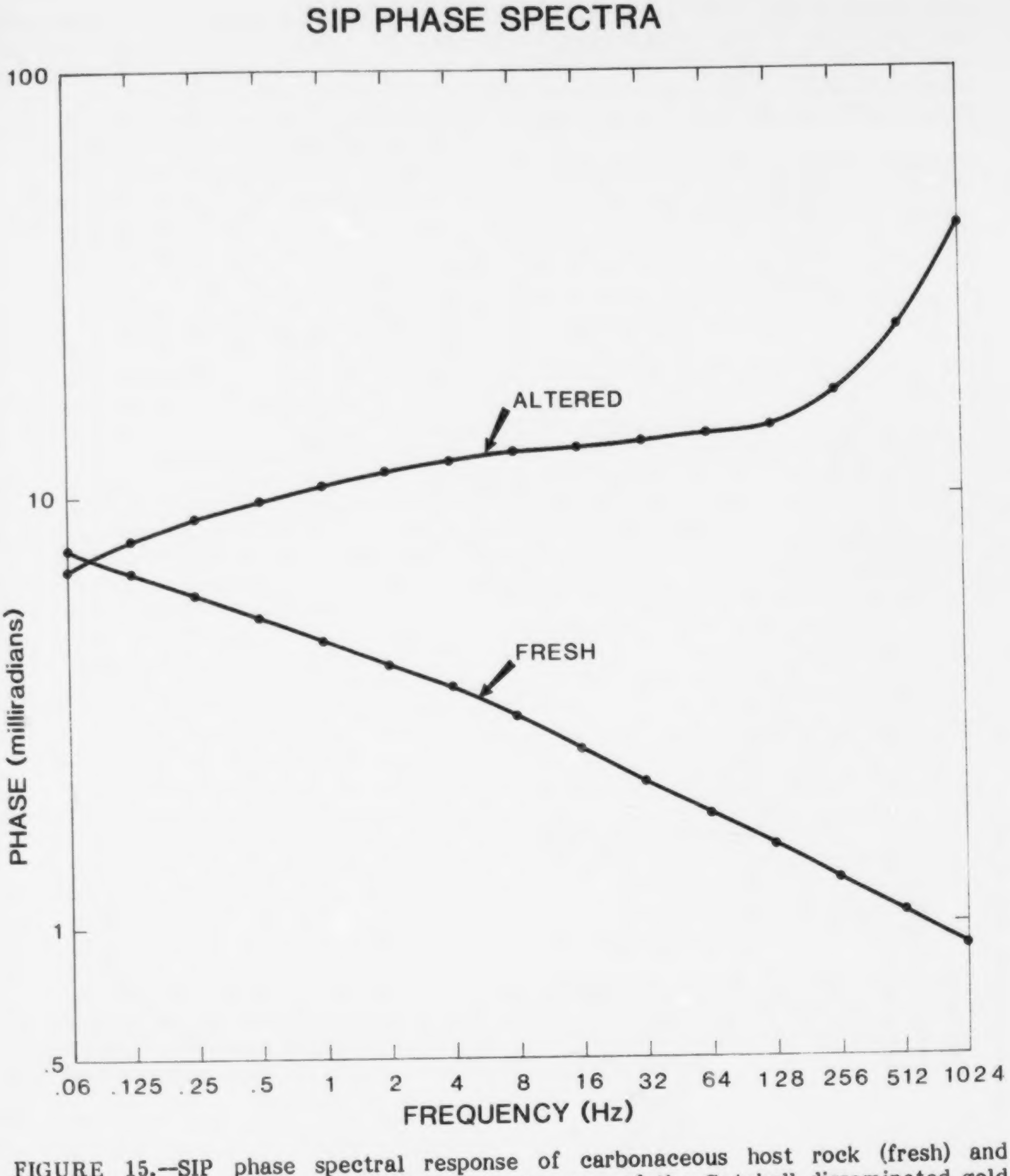

FIGURE 15.--SIP phase spectral response of carbonaceous host rock (fresh) and carbonaceous fault gouge (altered) in the area of the Getchell disseminated gold deposit in north-central Nevada.

The following example from the Ryan Hill study area in New Mexico illustrates the use of the AMT method for rapid studies having limited objectives. The study area lies within the southern Magdalena Mountains near Socorro, N. Mex. (fig. 16), near the edge of what is inferred to be a large concealed batholith (Mogollan Plateau Pluton). Rocks in the study areas are a sequence of Tertiary volcanic rocks of varying

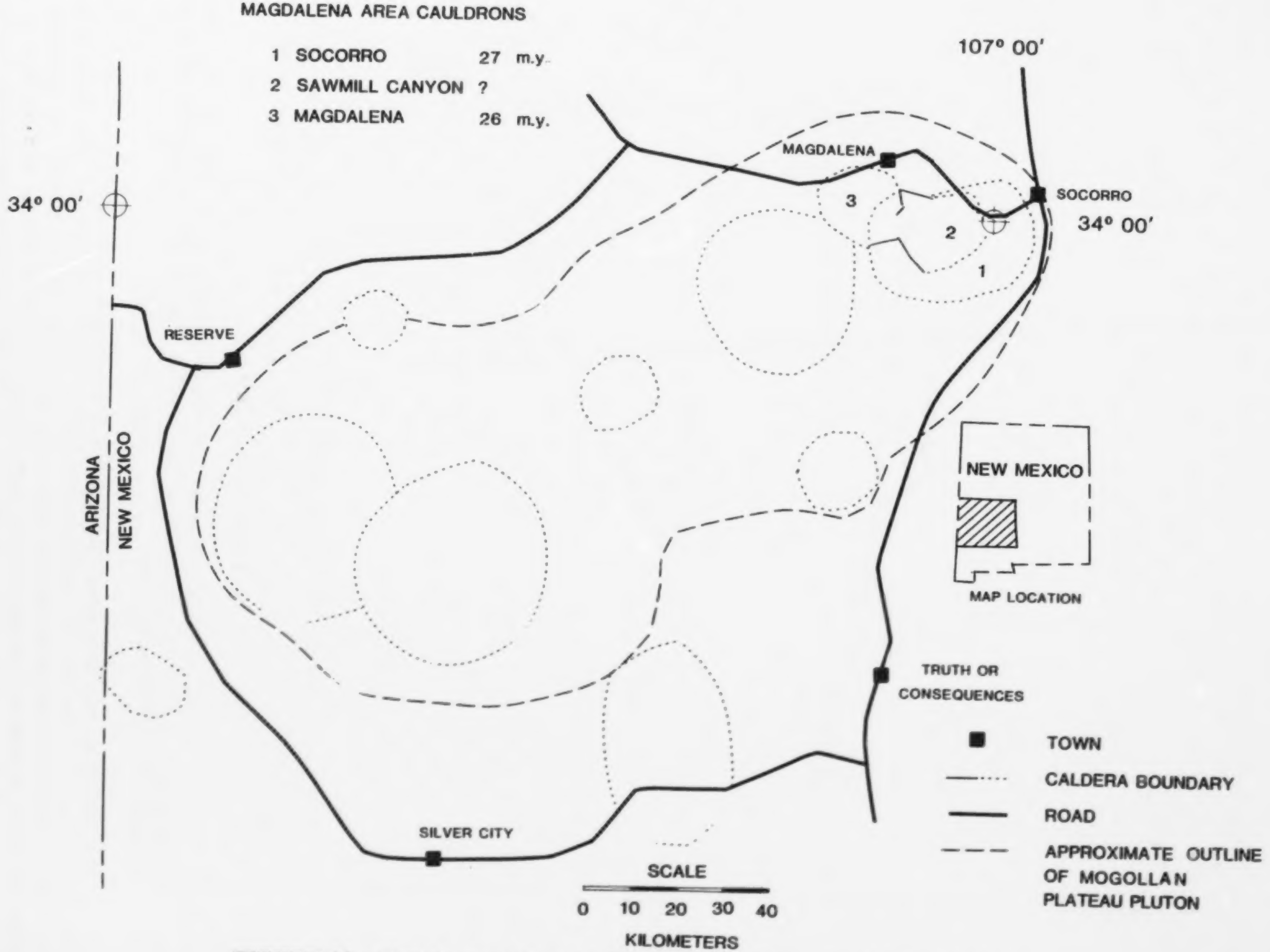
MAGDALENA AREA CAULDRONS
1 SOCORRO 27 m.y.
2 SAWMILL CANYON ?
3 MAGDALENA 26 m.y.
107° 00′
34° 00′
34° 00′
MAGDALENA
SOCORRO
1
2
3
RESERVE
ARIZONA
NEW MEXICO
NEW MEXICO
MAP LOCATION
TRUTH OR CONSEQUENCES
SILVER CITY
TOWN
CALDERA BOUNDARY
ROAD
APPROXIMATE OUTLINE OF MOGOLLAN PLATEAU PLUTON
SCALE
0 10 20 30 40
KILOMETERS

FIGURE 16.—Sketch map of part of the Mogollan Plateau of New Mexico.

composition and Tertiary and Quaternary alluvium (fig. 17). Two AMT traverses (one long and one short) were made. The data were interpreted by using a continuous one-dimensional Earth model and displayed as an electrical cross section (fig. 18). In areas where rapid lateral changes in resistivity occur, using a layered Earth model introduces errors in interpretation, but sections such as the one in figure 18 are nevertheless generally found to be qualitatively useful.

The lowest resistivities in the area are found at shallow depths under the alluvium at the eastern end of the long traverse. This area is just west of a region identified by Chapin and others (1978) as the site of a possible shallow magma chamber. Thus, the low-resistivity zone may represent a shallow hydrothermal system. Lithologies at this locality consist of Miocene claystone and mudstone and interbedded basalt infilling the Socorro cauldron. If a hydrothermal system is present, the lowest resistivities should be related to units containing the hottest water and the greatest degree of hydrothermal alteration.

A low-resistivity zone of limited depth occurs near stations 2 and 5 (fig. 18). Manganese deposits of hydrothermal origin occur at station 5; the low-resistivity zone is probably due to alteration in the rocks caused by hot spring activity.

The most interesting anomaly in the study area occurs near stations 4 and 21 (fig. 18). Although the resistivities here are not as low as those in the two anomalies just described, the zone is at depth where the resistivity of a large volume of rock is averaged. Locally, there may well be lower resistivities within the zone. In any case, this low-resistivity zone is in sharp contrast with higher resistivity rocks on either side. The zone may extend as far south as stations 9 and 10 (fig. 17), where a low-resistivity zone within the volcanic rocks was also identified. The anomaly at stations 4 and 21 is roughly at the lowest part of a regional aeromagnetic low that could be due to destruction of magnetite by alteration. Also, geochemical studies show anomalously high base and precious metals in the general vicinity of the AMT anomaly. It is reasonable to interpret the AMT anomaly as being caused by an altered and possibly mineralized zone at depth in the volcanic rocks. The presence of ash-fall tuffs is a possible explanation for the anomaly, but none have been observed in the study area.

A shallow, flat-lying, low-resistivity zone was found at the western end of the traverse. This zone also could be caused by a layer of ash-fall tuffs, if they occur in the section, or it could represent an altered and possibly mineralized zone.

The AMT survey of the Ryan Hill area required only a few days in the field, including time required for backpack traversing in a roadless area. The results had a significant influence on the assessment of the resource potential of the area. An equivalent IP survey of the area would probably have been more definitive but also much more costly.

In the examples given, a subjective evaluation could be made of AMT's contribution to the determination of subsurface lithology and structure. However, evaluation of inferences regarding potential mineralization, such as those made at Ryan Hill, would require additional information that is not available.

CONTINUING DEVELOPMENTS

The AMT and MT methods, which use energy from natural sources, and airborne methods, such as VLF EM, are inherently well suited to reconnaissance studies, and their use in mineral resource assessment is increasing. The MT method is starting to be used in CUSMAP projects in the Western United States to map the configuration of deep basins filled with conductive sediments and to map major structures that may control the distribution of mineral deposits. The conversion of AMT instruments from scalar to tensor measurements will probably lead to increased use of this method in complex areas.

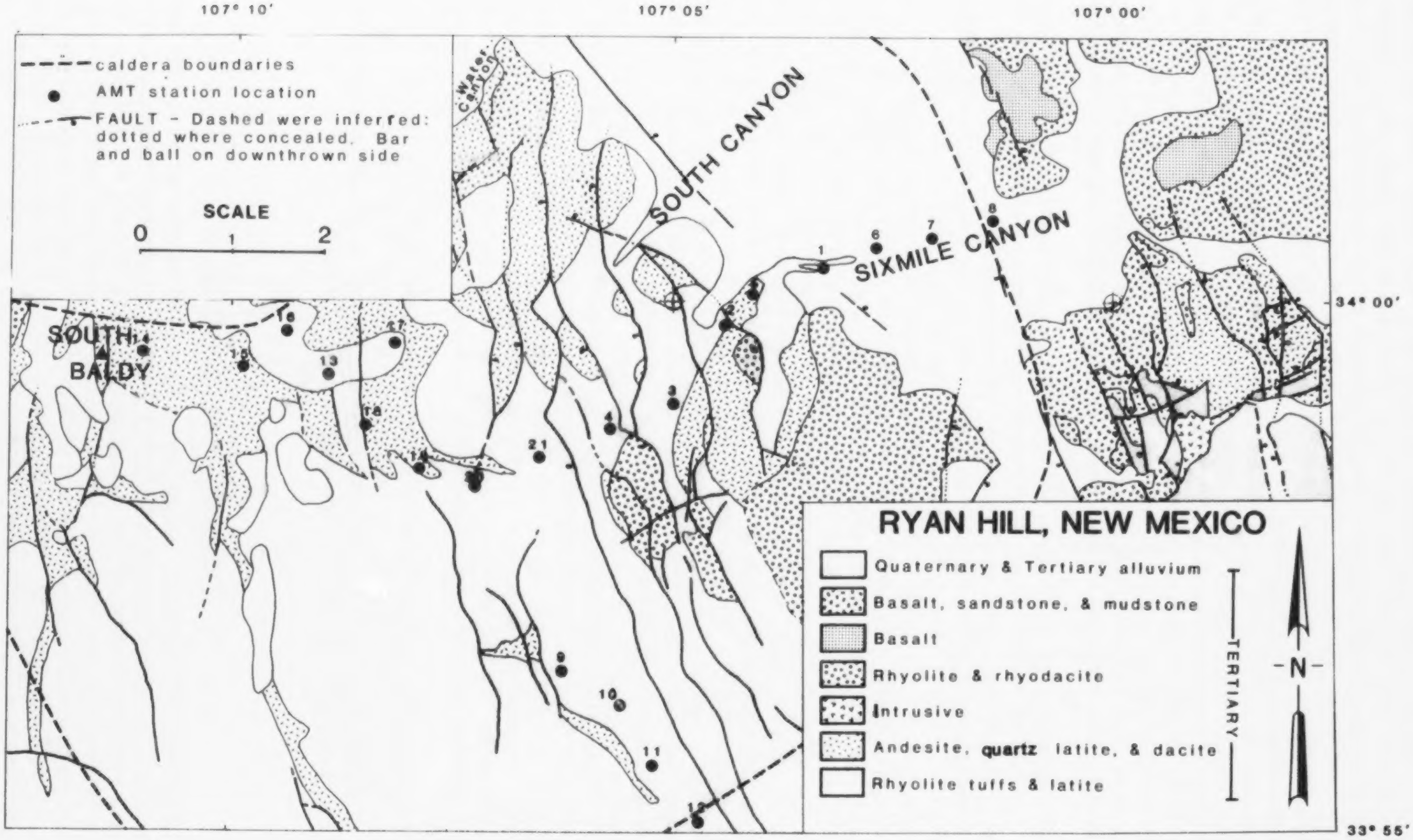
107° 10'
107° 05'
107° 00'
34° 00'
33° 55'
caldera boundaries
AMT station location
FAULT - Dashed were inferred: dotted where concealed. Bar and ball on downthrown side
SCALE
0
1
2
SOUTH CANYON
SIXMILE CANYON
Water Canyon
SOUTH BALDY
1
2
3
4
6
7
8
9
10
11
13
15
16
17
21
RYAN HILL, NEW MEXICO
Quaternary & Tertiary alluvium
Basalt, sandstone, & mudstone
Basalt
Rhyolite & rhyodacite
Intrusive
Andesite, quartz latite, & dacite
Rhyolite tuffs & latite
TERTIARY
N

FIGURE 17.—Simplified geologic map of Ryan Hill study area. Locations of AMT stations are indicated by solid circles.

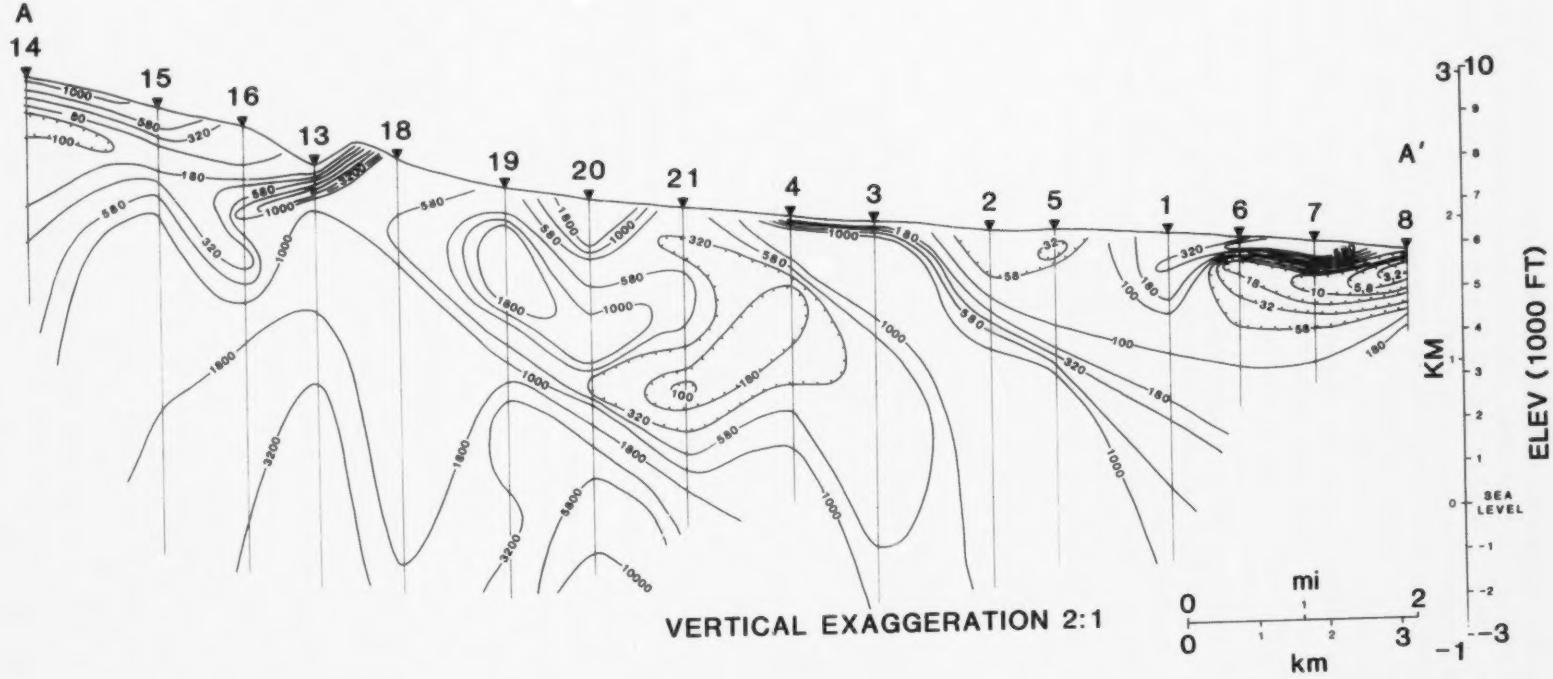

FIGURE 18.—AMT resistivity cross section of the Ryan Hill Roadless Area of New Mexico, based on one-dimensional inversions of each sounding. Triangles indicate station locations.

The need for an inexpensive airborne EM technique having a depth of investigation greater than that of VLF is apparent. The fields from 60-Hz power lines penetrate hundreds of meters, even in conductive surficial cover, and are a potential source of energy for airborne measurements. A receiver has been constructed, and experiments are underway to determine whether 60-Hz measurements from aircraft are feasible. If the method becomes operational, the receiver could be deployed in a light aircraft along with a magnetometer and VLF system.

One of the new frontiers in the application of geoelectrical methods is mineral resource assessment of the Exclusive Economic Zone offshore of the United States. A prototype IP system for ocean-bottom measurements has been assembled, and results from an initial survey are promising (J. Wynn, oral communication, 1985).

Improvements in processing, interpreting, and displaying geoelectrical data are just as important as advances in instrumentation. Part of the reason for the popularity of the dc resistivity sounding method is that the data can readily be transformed to show the subsurface variations of electrical resistivity, which is a fundamental rock property. Similar means for displaying other types of geoelectrical data are being developed along with computer modeling techniques to allow better quantitative interpretation of data from complex areas.

CONCLUSIONS

The examples included in this report demonstrate the wide variety of uses to which electrical methods can be put in mineral resource assessment. The results are unique in the sense that they could not have been obtained by any other geophysical method. The reasons for choosing electrical methods and the modes in which they are deployed can be quite different for mineral resource assessment and for mineral exploration. Potential field and remote sensing methods can be applied in a fairly routine way to the study of entire areas under assessment. In contrast, electrical methods are likely to be applied only to parts of an area or to resolve specific questions. The examples given here do not fully reflect the capabilities of some of the most recent techniques used in mineral exploration. To more fully use the capabilities of geoelectrical methods, development of effective but inexpensive electrical methods for use in mineral resource assessment must continue. Also, there is a need for objective evaluation of the effectiveness of geoelectrical methods as well as of other geophysical methods and strategies applied in mineral resource assessment.

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MULTIPLE DATA-SET INTEGRATION IN RESOURCE ASSESSMENT

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Geological Survey of Canada

ABSTRACT

Recent studies stressing two themes are reviewed. The first involves the design of data integration schemes adapted to investigate the characteristics and interrelations of geologic data sets; the second concerns detection of anomalies by removing from a data set variations that can be explained by known effects. Four cases are presented.

INTRODUCTION

This paper provides a condensed overview of four recent studies involving multiple data-set integration. Although the long-term goal of these studies was the quantitative appraisal of mineral resources, the short-term objectives did not include the direct prediction of mineral occurrences. Instead, the objective was to develop and adapt algorithms for integrating map data, tailored to answer specific geologic questions, and to take account of the special properties of various geologic data sets.

The approach here is thus not a regression in which the dependent variable is mineral occurrence. Applications of this type of multivariate analysis are discussed elsewhere in this volume (see Agterberg, this volume). Nor are we applying mineral deposit model concepts to provide weights for linearly adding multiple images together. Instead, we are exploring mapped quantities, with a view to providing a better understanding of their interrelationships.

Thus, in case study A, the relation between bedrock geology and surficial geochemistry is used to remove the geochemical variation explained by the geology. After the resulting residuals have been corrected for dilution, they can be displayed as an image, which contains information about other factors such as glacial transport, hydroxide scavenging, and mineralization.

Case study B involves a method for evaluating the spatial interdependence of mineral deposits and lineaments. Linear features can provide useful clues to mineralization, and this approach seeks to determine which (if any) lineament directions are important, whether lineament density is significant, and what sampling area should be used for mapping lineament density.

Case study C investigates the interrelation between Landsat multispectral scanner (MSS) data and mapped geologic units by means of multivariate statistics. It is hardly surprising that the spectral response in an area having extensive glacial cover is dominated by the effects of glacial terrane types. However, if pixels are selected carefully in areas that have little or no glacial cover, it is possible to obtain some discrimination between bedrock lithologies by using MSS.

Finally, case study D discusses some ongoing work with airborne multispectral data, collected by using the multispectral electro-optical imaging scanner (MEIS) developed in Canada. Images flown over an area containing a documented geochemical anomaly are processed to detect vegetation stress. This procedure involves image analysis to select tree crowns and a method for modeling the spectral response of vegetation to detect spectral shift due to stress.

Because the hardware and software used for image processing and multiple data-set integration are undergoing rapid development, much of the work on these studies has been carried out by a variety of programs and machines. Table 1 summarizes the data sets used in each case study, the types of data capture, the hardware and software used for analysis, and the types of hard-copy image output. Although image-processing systems already developed offer efficient, fast analysis of image data, they are not flexible enough to allow "hands-on" development of the new algorithms that are vital in a research environment. However, writing new software for every new problem is clearly inefficient. Our solution has been to "mix and match," using a variety of the hardware devices and software systems available in Ottawa.

CASE STUDY A: INTEGRATION OF BEDROCK GEOLOGIC DATA WITH STREAM GEOCHEMICAL DATA

The data sets used in case study A comprise (1) a map of bedrock geology, digitized to produce a raster image, (2) a topographic map showing sample locations, and (3) a digital data base containing chemical analyses for each sample.

The catchment basin upstream from each sample location is outlined from the geologic map and digitized. In the studies carried out to date (Bonham-Carter and Goodfellow, 1984, in press; Bonham-Carter and others, in press), this step has not been automated, although we are currently working on the automatic delineation of catchment basins from a digital elevation model.

The digital intersection of the geologic map image and the catchment basin image yields the areal proportion of each map unit in each basin. These data are used to augment the geochemical data base, so that each sample is associated with variables that describe the geologic composition of the associated catchment basin, as well as with variables that describe the geochemical composition of the sample.

A simple linear model is used to predict the log element content of each sample as a function of the areal proportion of rock types. The coefficients of the model are determined by least-squares regression, which minimizes the sum of squared differences between observed and predicted element contents. In the Nahanni River area study in northern Canada (Bonham-Carter and Goodfellow, 1986), between 60 and 15 percent of the total variance of an element was explained by geology in this way, depending on the element. For the Cobequid Highlands study in Nova Scotia (Bonham-Carter and others, in press), between 65 and 25 percent of the total variance was similarly explained.

The residuals (observed element content minus predicted element content) can be adjusted for the effects of varying catchment basin size to yield "mineralization ratings" for each sample location. Colored images, in which mineralization rating values are assigned to each catchment basin, can be produced for each element. The information contained in these images about each element reflects the combined effect of several factors, including glacial transport, metal scavenging in the secondary environment by iron and manganese hydroxides, and the presence of mineralization.

For the Nahanni area, Bonham-Carter and Goodfellow (1986) showed that the mineralization ratings are better than raw data values as predictors of known lead and zinc deposits. Furthermore, if the mineralization ratings of zinc in water and zinc in sediment are used together, known deposits can be predicted almost as well as they are when only lead mineralization ratings are used. Because the known deposits are all exposed at the surface, lead is eroded directly in streams as clastic grains. Zinc is much more effective in exploring for buried lead-zinc deposits, however, since it is highly mobile in solution, whereas lead is relatively insoluble.

TABLE 1.—Summary of data sets, methods of data capture, and hardware and software systems used for studies discussed in this paper

Data sets	Method of data capture	Image processing	Statistical processing	Image output
		Case study A		
Geologic map---------	Raster scanning[1]	Special-purpose FORTRAN routines on CYBER.	SPSS on CYBER	Applicon, Optronics[1]
Catchment basins-----	Raster scanning[1]		SPSS on CYBER	
Geochemical data-----	Existing database		SPSS on CYBER	
		Case study B		
Landsat MSS---------	CCT[2]	Lineament enhancement on DIPIX[3] system.	Special-purpose FORTRAN routines on CYBER.	Calcomp
Seasat---------------	CCT[2]			Calcomp
Lineaments-----------	Manual line following.[4]			Calcomp
Mineral occurrences--	Existing data base.			Calcomp

Case study C				
Geologic map--------	Digitizing tablet,[4] GIAPP.[5]	CIAS IMAGE 100.[6]	SPSS on CYBER	Applicon
LandsatMSS----------	CCT[2]	CIAS IMAGE 100[6].	SPSS on CYBER	Versatec
Case study D				
MEIS----------------	CCT[2]	MORPHOLOG on VAX.[3]		Tektronix[7] ink-jet plotter.[7]
Geochemistry---------	Digitizing tablet,[4] Chromatics.[7]	BIAS on Chromatics.[7]		Tektronix[7] ink-jet plotter.

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[1] System used at Canada Lands Data Systems, Lands Directorate, Environment Canada. Optronics laser scanner used both for raster input and in "playback" mode for output Bonham-Carter and others, 1985b).

[2] Computer-compatible tape (products of Canada Centre for Remote Sensing).

[3] DIPIX system at RADARSAT office, Canada Centre for Remote Sensing.

[4] Manual digitizing system used by Geological Survey of Canada.

[5] Image analysis package developed by Fabbri (1984) at Geological Survey of Canada and operated on a variety of computers.

[6] Canada Centre for Remote Sensing Image Analysis System.

[7] Chromatics 7900 is a stand-alone color graphics computer with digitizing tablet and Tektronix ink-jet plotter used by Geological Survey of Canada; uses BIAS, an image analysis package in FORTRAN.

CASE STUDY B: SPATIAL ASSOCIATION OF GOLD OCCURRENCES AND LINEAMENTS

Landsat MSS and Seasat (radar) images of an area in central Nova Scotia were processed to enhance linear features, (Harris, 1984). Lineaments were drawn by hand on the enhanced images and subsequently digitized in vector format by line following on a digitizing table. The UTM coordinates of gold deposits were taken from Ponsford and Lyttle (1984). The geologic map of the area was digitized, and a raster image of four lithologic units was produced.

To test the hypothesis that gold occurrences are spatially independent of lineaments, a program was written to:

1. Measure the distance from each gold occurrence to the 1, 2,...,kth nearest lineament. Lineaments are approximated by a series of connected straight-line segments.
2. Determine the cumulative distance distribution expressing the proportion of observed gold occurrences that occur within a given distance of the kth nearest lineament.
3. Estimate the cumulative expected distance distribution that describes the probability that a random point will lie within a given distance of the observed lineaments.
4. Test the hypothesis that the observed distance distribution is greater than the expected distribution by using a one-tailed Kolmogorov-Smirnov statistic.
5. Repeat steps 1 through 4 for selected lineament directions.

Step 3 is carried out by means of a Monte Carlo simulation. A large number of points are generated by a random number generator, under the constraint that points can occur only within the boundaries of chosen lithologic units.

Figure 1 shows a graph of observed and calculated distance distributions of gold occurrences and Seasat lineaments oriented NNW-NW. The hypothesis that the gold occurrences are spatially independent of these lineaments can be rejected at the 95-percent confidence level (Bonham-Carter and others, 1985a).

Experiments with lineaments in other directions showed that Landsat lineaments oriented ENE are also spatially associated with gold occurrences, whereas other orientations showed no association. A further test showed no statistical relation between gold occurrences and lineaments in all directions.

We conclude that, if lineament neighborhood is to be used as a mapped variable for resource assessment for gold, separation of lineaments by direction is vital. In another study, Bonham-Carter (1985) showed that lineament density, as well as direction, is an important variable for predicting gold occurrences in the Timmins-Kirkland Lake area.

CASE STUDY C: RELATION BETWEEN LANDSAT MSS DATA AND GEOLOGY, BAKER LAKE, NORTHWEST TERRITORIES

A raster image of bedrock geology in the Baker Lake area of the Northwest Territories was registered with a Landsat MSS image that had been resampled to 500-pixels. The Landsat image was classified to yield the surficial geology units defined on an existing map of surficial geology. Between 50 and 70 percent of the Landsat pixels were correctly assigned to the classifications shown on the surficial geologic map. This success rate confirmed the general visual similarities between the MSS imagery and the surficial geologic map.

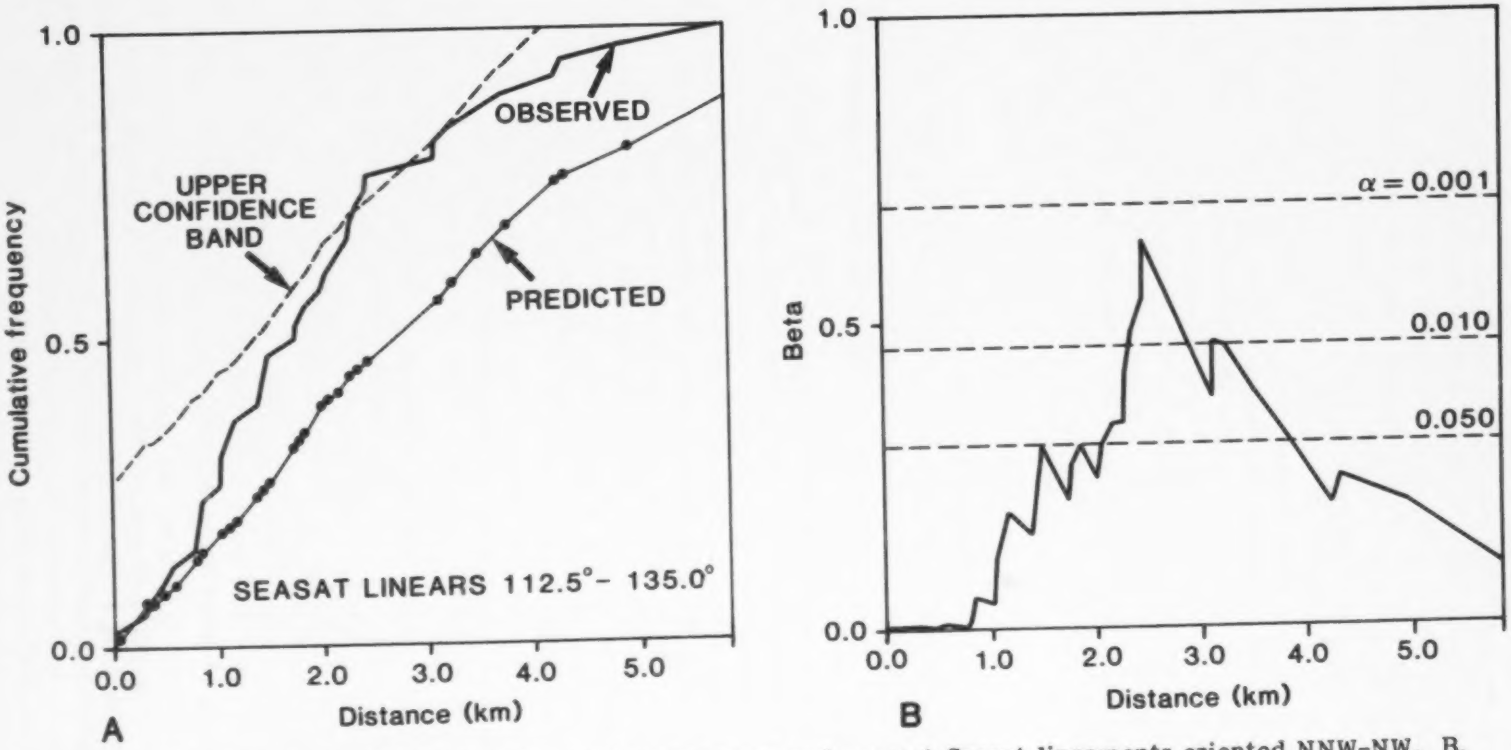

FIGURE 1.—A, Distance distribution for gold occurrences and nearest Seasat lineaments oriented NNW-NW. B, Test statistic β plotted against distance. Occurrences falling within 3 km of the nearest lineament are closer than one would expect if lineaments and gold occurrences are generated by independent processes.

Another question was whether one can discriminate between bedrock units on the basis of their spectral responses. An initial experiment using the whole image indicated that no statistical relation existed between geology and MSS data. The hypothesis that bedrock units might be more readily discriminated in areas where the surficial cover was very thin or nonexistent was then tested, by selecting such pixels (about 5 percent of the whole image) and using their characteristic spectral response.

A multiple linear discriminant model (also confirmed by a logistic model) using the four MSS bands, simple ratios of MSS bands, and various combination of band ratios showed that three groups of bedrock units could be correctly identified in 66 percent of the cases, in comparison with the 33-percent success rate expected if the geologic classification and the spectral response are independent of each other (Bonham-Carter and Rencz, 1982). We suspect that this degree of discrimination is possible because of subtle differences in the sparse vegetation over these sites and differences in the spectral responses of the rocks. It can be concluded that, in this type of terrane, MSS imagery can be useful for broad lithologic discrimination, but only if areas having little or no glacial cover are selected.

CASE STUDY D: USING AIRBORNE MEIS IMAGERY TO DETECT VEGETATION STRESS DUE TO A GEOCHEMICAL ANOMALY

MEIS, a new Canadian airborne scanner, is being tested for detecting vegetation stress. Some initial results from a test area in Algonquin Park, Ontario (Ford and others, 1984), indicate that the spectral response of trees growing in an area where geochemically anomalous till is present is significantly different from that of trees growing in a background area. We report here on some ongoing work designed to evaluate the initial results.

Two problems are being addressed. First, is it possible to improve detection of vegetation stress by using only treetops to study the spectral differences between trees from mineralized areas and those from unmineralized areas? The image data has a pixel size of 0.8 m on the ground, so that individual trees can be seen on the image. Second, can the spectral response at each pixel be modeled to yield a small number of parameters that would act as stress indicators, so that the amount of data needed can be reduced (MEIS uses 5 to 8 wavebands).

Simple thresholding of any one spectral band (or combination of bands) is inadequate for detecting tree crowns. We have shown that the following algorithm works reasonably well for picking out the crowns:

1. Perform a gray-tone image dilation followed by erosion (Serra, 1982). If A is the original image and B is a structuring element, these operations can be algebraically described as $(A \oplus nB) \ominus nB \rightarrow C$.
2. Subtract the resulting image C from the original (a process known as "top-hat" transformation) and threshold it.
3. The resulting image, after further cleaning, consists of a mask of treetop pixels equal to 1 and other pixels equal to 0. This tree-top mask is then multiplied by the spectral images, and thus only the treetop data are selected for further analysis.

The second problem (modeling the spectral data) has been studied by Hare and others (1985), and we are following a similar approach. After the spectral data have been converted to reflectance values, a model similar in form to an inverted Gaussian curve is fitted by nonlinear least squares to the reflectance values. Parameters can be chosen for this model to characterize the "red shift" caused by vegetation stress.

Finally, images of the stress parameters, masked to treetops only, are compared with an image of till geochemical data.

CONCLUSIONS

Instead of attempting to directly predict or model mineral deposit favorability, the quantitative identification of anomalies in regional survey data provides an empirical method of resource assessment. The "mineralization rating" approach, which uses catchment basin analysis of stream geochemical data, is an example of this method, which can be used without prior knowledge of actual mineral occurrences.

Statistics show that gold occurrences (Meguma Terrane in Nova Scotia and Timmins-Kirkland Lake in Ontario) are spatially associated with lineaments oriented in particular directions and, in some cases, are related to lineament density. If lineaments could be meaningfully and repeatably detected on imagery, such data would comprise an inexpensive regional survey tool to be used in resource studies and exploration.

Remotely sensed multispectral data may ultimately be useful for resource assessment but only if suitable methods of data compression can be developed and if processing methods that can select certain features of an image are used. In case study C, for example, the relation between geology and MSS data can be seen only when "bare-rock" pixels are selected. In case study D, the "red shift" can be effectively recognized only when "treetop" pixels are selected.

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MINERAL RESOURCE ASSESSMENT OF THE SAN ISABEL NATIONAL FOREST, COLORADO: A PROTOTYPE FOR 1:250,000-SCALE MULTIDISCIPLINARY ASSESSMENTS "FROM THE LITERATURE"

By Richard B. Taylor[1] and John S. Dersch[2]

ABSTRACT

This mineral resource assessment of the San Isabel National Forest, based entirely on published data and presented as U.S. Geological Survey Bulletin 1638, is the prototype for a series of assessments that use available geologic, geochemical, and geophysical information. Land use planning requires evaluating the mineral resource potential of Federal lands at a rate exceeding the capacity, both budgetary and personnel, of the U.S. Geological Survey (USGS) to conduct field surveys. This study was undertaken to establish a methodology and to test the feasibility of "literature assessments" at a scale of 1:250,000, which was chosen to balance planning needs against the detail available from published information. The San Isabel National Forest covers 1,940 mi^2 in the southern Rocky Mountains and extends 160 mi south-southeast from north of Leadville, Colo., to south of the Spanish Peaks. It was selected for this study because of the diversity of its mineral deposits, including a part of the Colorado mineral belt, and because the amount of information available is typical of what is available for much of the West. Responsibility for assessing locatable and leasable minerals was taken by the USGS; that for salable minerals was taken by the U.S. Forest Service. The project was conducted jointly by these two agencies, and information was shared throughout the work.

The procedures used for this assessment were fundamentally similar to those used in the initial phase of any mineral resource assessment project, except that the results have been published. As expected, the quality and nature of the assessment data vary from place to place.

Available geologic maps were collected, and a coherent geologic map was compiled at 1:250,000 scale from the disparate pieces. Compilation started with the 1:250,000-scale maps of the Leadville, Montrose, Pueblo, and Trinidad 1°x2° quadrangles. These maps were supplemented with more detailed maps, including those from graduate theses and recent mineral surveys of wilderness study areas.

Available geochemical and geophysical data were also collected, and selected parts were compiled at 1:250,000 scale. Sets of National Uranium Resource Evaluation geochemical data from the four stream-sediment surveys that covered the area were examined, and 11 elements (Co, Cu, Cr, Fe, Mn, Ni, Pb, Sn, Th, U, and W) were selected as useful and sufficiently reliable analytically for assessment purposes. Geochemical data from wilderness surveys were examined but not recompiled at the scale of the San Isabel study. Regional gravity and aeromagnetic maps were collected for the entire area, and selected maps were reduced to 1:250,000 scale. No attempt was made to recompile and recontour data.

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[1] U.S. Geological Survey.

[2] U.S. Forest Service.

The information and recommendations contained in this report provide a basis for long-range planning of exploration and development strategy in Colombia, for national decisions on mineral policy and land use, and for establishing research goals. This prototype project outlines a practical approach to assessing the mineral resources of an entire country when both time and basic information are limited.

Data on mineral deposits were collected and examined. These data included published mine and district descriptions, computerized data files, and mine and prospect location information from 1:24,000-scale topographic maps replotted at 1:250,000 scale.

Occurrence and genetic resource models, called "deposit types" in this report, were constructed; 17 deposit types were used. The models are based on deposits both within and outside the forest.

Terrane in the forest boundaries was evaluated, and levels of mineral resource potential and of certainty of assessment were assigned to areas for specific commodities on the basis of specified deposit types.

Results were published as text and 1:250,000-scale geologic and mineral resource maps.

The credibility of an assessment "from the literature" relies in part on the adequacy of the literature and on the time available for search, compilation, and interpretation and in part on the availability of geologists who have experience in the area, so that the interpretations of compiled data are more than just "words" and "numbers."

COLOMBIAN MINERAL RESOURCE ASSESSMENT

By Carroll Ann Hodges, Dennis P. Cox, Donald A. Singer,
James E. Case, Byron R. Berger, and John P. Albers
U.S. Geological Survey

ABSTRACT

An assessment of the nonfuel, largely metallic mineral resources of Colombia was begun in July 1982 by the U.S. Geological Survey and the Instituto Nacional de Investigaciones Geologico-Mineras (INGEOMINAS). Major goals of this 1-year cooperative project were (1) to synthesize data on the mineral resources of Colombia, (2) to identify terranes or tracts permissive for specific mineral deposit types, (3) to provide guidelines for exploration based on deposit models, and (4) to derive probabilistic estimates for grades and tonnages of undiscovered deposits. The fundamental assumption on which the project was based is that geologic terranes permissive for particular types of mineral deposits can be identified and delineated in poorly explored areas by drawing analogies with better known areas having similar geologic environments.

Existing geologic data and new mapping by INGEOMINAS, together with a lithostratigraphic terrane map developed during this study, were used to produce a 1:2,000,000-scale mineral resource map of the entire country. Analysis of mineral occurrence data from INGEOMINAS files and discussions with Colombian geologists enabled us to draw up a list of deposit types either identified or suspected; tracts in which the geologic environment is permissive for these deposit types were outlined on the map. Our report accompanying the map presented detailed descriptions of selected deposit types, including possibilities for their occurrence in Colombia, as well as exploration guides and recommendations. Two appendices, each prepared specifically for this project, provided compilations of ore deposit models and grade-tonnage models; these attachments were keyed to each other and cross referenced in the text. The following example, drawn from our investigations in Colombia, illustrates the general approach that was used.

The Cordillera Occidental tract is accreted oceanic terrane, as characterized by its geophysical signature and by Mesozoic and Paleogene ophiolite and primitive magmatic arc assemblages. Cyprus-type massive sulfide deposits tend to occur preferentially in such geologic environments, most commonly in association with pillow basalts and diabase dikes. Three recorded occurrences of stratiform sulfides within this province indicate that Cyprus-type ore-forming processes have been active. Using available geologic, metallogenic, geophysical, and geochemical data, we outlined other tracts permissive for Cyprus-type deposits on the 1:2,000,000-scale map. To estimate the possible grades and tonnages of new deposits that might occur within these designated tracts, we referred to the model developed for Cyprus-type deposits on the basis of worldwide data for 49 such deposits. For any Cyprus-type deposits that may exist within the tracts delineated in Colombia, similar grades and tonnages can be expected. Among the other deposit types treated in this way were sedimentary manganese, sedimentary exhalative lead-zinc, and hot spring gold-silver.

During this collaboration, our Colombian colleagues expressed keen interest in geochemical techniques, specifically with respect to gold exploration; accordingly, a series of workshops on appropriate procedures was subsequently presented in several regional INGEOMINAS offices by Byron Berger.

FINDER: A METHOD OF INTEGRATING SPATIAL AND FREQUENCY INFORMATION IN RESOURCE ASSESSMENTS

By Donald A. Singer[1] and Ryoishi Kouda[2]

ABSTRACT

FINDER is a computer program intended to aid geologists in assessing and searching for ore deposits of particular types. One or more well-studied deposits serve as a control in which the means and standard deviations of each variable are estimated near a deposit (in a mineralized area) and away from the deposit (in a barren area). Up to four independent variables reflecting geologic, geochemical, or geophysical information can be used. Circular, elliptical, and annular target variables are possible, and preferred orientations are allowed. The normal probability density function, Bayesian statistics, and area of influence method are used to integrate spatial and frequency data from the study area to produce a map of the probabilities of target (deposit) centers and to estimate the number of deposits present.

The performance of FINDER was tested in the Hokuroku district of Japan. FINDER rediscovered four of the five known Kuroko deposits located in high-probability areas by using the variable Na_2O depletion. The only deposit missed was much smaller than the control deposit. Several new areas in the district were also identified as favorable deposit centers.

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QUANTITATIVE ESTIMATION OF UNDISCOVERED MINERAL RESOURCES: CASE STUDY OF U.S. FOREST SERVICE WILDERNESS TRACTS IN THE PACIFIC MOUNTAIN SYSTEM

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ABSTRACT

The need of land managers and planners for more quantitative measures of mineral values has prompted scientists at the U.S. Geological Survey (USGS)to test a probabilistic method of mineral resource assessment on a portion of the wilderness lands that the USGS has studied over the past 20 years. A quantitative estimate of undiscovered mineral resources is made by linking the techniques of subjective estimation, geologic mineral deposit models, and Monte Carlo simulation. The study, which uses grade-tonnage and occurrence models for 21 geologic deposit types, considers 91 U.S. Forest Service wilderness tracts in California, Nevada, Oregon, and Washington (the Pacific Mountain System). Estimates of the amounts of the 11 metals contained in undiscovered mineral deposits of the types studied range from negligible to enough to satisfy several years of U.S. consumption. Although these estimates are limited to metals contained in undiscovered deposits of a small number of metallic mineral deposit types, the assessment procedure can be expanded by using additional deposit models and information about identified mineral resources. Models of economic processes such as exploration, development, and production can then be applied.

IMPLICATIONS OF RECENT REMOTE SENSING DEVELOPMENTS FOR MINERAL RESOURCE STUDIES

By Gary L. Raines
U.S. Geological Survey

ABSTRACT

Current remote sensing research indicates that analysis of high-spectral-resolution aircraft and satellite images can substantially increase applications. Visible and near-infrared reflectance measurements permit identification of geochemically stressed plants and many Fe^{2+}, Fe^{3+}, OH^{-1}, CO_3^{-1}, and rare-earth-element minerals. Midinfrared emittance measurements allow additional important distinctions, especially among silicates and between silicates and carbonates.

Airborne high-spectral-resolution reflectance measurements, acquired commercially for mineral assessment, are integrated with other data in the following manner. Initially, laboratory analysis of Landsat Multispectral Scanner data defines the distribution of limonitic rocks. Analysis of Thematic Mapper data, as data availability permits, identifies and maps the distribution of clay-rich rocks. Through brief field studies of the limonitic and clay-rich areas, hydrothermally altered rocks are differentiated from other sources of limonite and clay. Field spectral reflectance measurements of mineralogic identification and selective sampling for geochemical and petrographic analysis are also included. For promising areas, airborne spectrometer surveys then define the distribution of minerals that indicate varying geochemical and hydrothermal conditions. Until recently, airborne systems have been nonimaging profiling systems, but high-spectral-resolution imaging systems are now available. Also, imaging spectrometers will fly in space during the next decade.

Once a coherent surficial hydrothermal alteration pattern has been defined, audiomagnetotelluric and telluric traversing surveys then define the alteration pattern at depth. Combining the geophysical information with the remote sensing analyses rapidly provides a three-dimensional picture of the characteristics of these large hydrothermal systems for use in mineral deposit models.

DISCUSSION GROUP 2A

METALLOGENY AS A FIRST STEP TO MINERAL ASSESSMENTS ON PUBLIC LANDS

By Donald F. Sangster[1] and William F. Cannon[2]

SUMMARY

The limiting factor in metallogenic resource assessment is generally the regional geology information base. The use of metallogeny as a technique would be substantially improved if detailed geologic maps were more readily available. Also, future detailed mapping must be cognizant of important metallogenic features and modern tectonic concepts.

Metallogenic analysis is important throughout a mineral assessment study but is most effective in the initial planning and final synthesis stages of the assessment procedure. Regional metallogeny promises to provide vital data for estimating expected numbers of deposits and establishing valid tonnage and grade distributions. However, quantification of such estimates is an ideal not yet fully realized. At present, it is a research topic and only rarely reliable enough to form a basis for public policy.

Application of metallogeny is the most effective means of combining regional geology and mineral deposit information for an initial assessment of the mineral potential in a given area. The assessment procedure can consist of extrapolating metallogenic data from adjoining areas into a study area, or it can be based on the principle of conceptual models of deposit types not found in or adjacent to the study area. The extremely flexible procedure is capable of integrating a variety of levels and types of information and requires no machine processing of data.

To examine the use of metallogeny in resource assessments, the group selected four issues for discussion.

ISSUE 1: TO WHAT EXTENT ARE THE REGIONAL DATA BASE AND CURRENT DEPOSIT MODELS LIMITING FACTORS IN METALLOGENIC RESOURCE ASSESSMENTS?

Because metallogenic analysis is done by interpreting the relations between regional geology and ore genesis, the accuracy of the analysis depends on both the completeness of the deposit model and the regional geologic detail available. A typical geologic map contains data on lithology, age, structure, and, in some cases, the origin or tectonic setting of map units. These parameters are a minimum requirement for application of most mineral deposit models. That is, if a model exists, it contains at the very least information on such regional geologic features as host rock type, age ranges of deposits, and tectonic setting. Therefore, for virtually any deposit model, even the most rudimentary, the typical geologic map is only minimally satisfactory for metallogenic interpretation. In many cases, deposit models recognize criteria far more numerous and sophisticated than those normally displayed on existing geologic maps. The science of deposit modeling has far outstripped our ability to apply all mineral deposit criteria in metallogenic analysis. The more sophisticated deposit models are most useful in larger scale, more detailed studies or in exploration rather than in regional metallogeny. Most deposit models do not include geophysical criteria, so, to the extent that the regional data base includes geophysics, there may be shortcomings in the existing models.

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Conclusion

The limiting factor in metallogenic resource assessment is generally the regional geology information base.

Recommendations

1. The application of metallogenic principles would be substantially improved if detailed geologic maps were more readily available.
2. Future detailed mapping must be cognizant of important metallogenic features and modern tectonic concepts.

ISSUE 2: AT WHAT POINT(S) IN THE ASSESSMENT PROCEDURE IS METALLOGENY MOST EFFFECTIVE?

Although metallogenic interpretation is an iterative process, continually being refined during the course of an assessment study, it is most important as both a first and a final step.

First Step

At this stage, the study area can be set in its broader regional metallogenic context. A preliminary metallogenic analysis using available data on geology, mineral deposits, and deposit models from both the study area and the surrounding region is important as a planning tool. The analysis will identify deposit types of concern and terranes of metallogenic interest and will evaluate the adequacy of existing data to make a resource assessment. Information gaps identified at this stage will serve as valuable input to project planning. For some areas, this first step will also be the only step in a resource assessment.

Final Step

The final resource assessment, which is an integration of all geoscience data collected during the assessment program, can most effectively be synthesized in metallogenic terms at this stage.

Conclusion

Metallogenic analysis is important throughout a mineral assessment study but is most effective in the initial planning and final synthesis stages of the assessment procedure.

Recommendations

1. A preliminary metallogenic study should constitute a major part of the first stage in a mineral assessment program.
2. For longer term programs (3-5 years), preliminary metallogenic syntheses should be published to encourage peer review and public input at an early stage.
3. A metallogenic synthesis integrating all geoscience data gathered during the program will serve as a convenient and concise vehicle by which to portray mineral resource potential.
4. All final resource assessment reports should discuss the regional metallogenic setting of the study area and not focus solely on data acquired within the area.

ISSUE 3A: CAN THE METALLOGENIC APPROACH LEAD TO QUANTITATIVE ASSESSMENTS?

Metallogeny promisea to assist in estimating the number of undiscovered deposits as well as the deposit tonnage and grade distributions in each tract being assessed. Although substantial research will be required to provide definitive answers, we feel that it might be possible to estimate the expected number of deposits through a combination of studies based on the average number of deposits per unit area of metallogenic province and studies of the spatial distribution of deposits within a metallogenic unit. Examination of well-explored areas, for instance, could yield values for numbers of deposits per unit area as well as information on how deposits are distributed spatially (uniform, random, clustered).

Another question to be researched is the degree to which the tonnage and grade distribution of a metallogenic province are unique Should tonnage-grade models developed from worldwide data be applied to a single metallogenic province, or must attempts be made to develop tonnage-grade data for each province? We know of at least one case in which application of a worldwide model would have led to serious error in resource estimates. Tonnage and grade compilations of about 500 podiform chromite deposits in California and Oregon yielded a tonnage distribution far different than that of the worldwide distribution. Deposits in ultramafic complexes in the Philippines and Turkey apparently are much larger than those present in otherwise similar rocks in California and Oregon. On the other hand, other deposit types (for instance, volcanogenic massive sulfides) appear to have comparable tonnage and grade characteristics everywhere that they have been studied. Therefore, the use of tonnage-grade models in quantitative resource estimates must be tested to determine to what extent the distribution in the province being studied is compatible with worldwide data.

Conclusion

Regional metallogeny promises to provide vital data for estimating expected numbers of deposits as well as for establishing valid tonnage-grade distributions.

Recommendations

1. Research is required to develop techniques for estimating, in probabilistic terms, expected number of deposits in metallogenic domains and the spatial distribution characteristics of deposits.
2. Tonnage-grade models should be carefully reexamined to determine whether worldwide data should be applied to all metallogenic provinces or whether each province has its own unique character.

ISSUE 3B: ARE QUANTITATIVE ASSESSMENTS DESIRABLE AND NECESSARY?

In an idealistic sense, quantitative resource estimates are both desirable and necessary to provide the data required to guide public policy. Policy decisions constantly deal with questions about the adequacy of mineral supplies or the value of minerals versus the value of other resources (for example, timber, grazing, recreation). In a practical sense, however, quantification is still in the research stage; it is not yet useful for establishing public policy. In some cases, sound quantitative estimates can be made by combining extensive data with subjective probability estimates made by knowledgeable, experienced economic geologists. In too many instances at present, however, the uncertainties of quantification overwhelm the usefulness of the result; improvements in both data and theory are needed before quantitative techniques will be widely accepted.

One immediate problem is that mineral data are commonly discounted in making land use decisions, because their qualitative nature is not easily compared with the quantitative data widely available for other resources. Quantification of resource estimates is, therefore, desirable in all cases where reasonable confidence can be demonstrated, to help ensure that potential mineral value will receive an equitable consideration in land use decisions.

Conclusions

Quantification of resource estimates is an ideal not yet fully realized. At present, it is a research topic and only rarely reliable enough to form a basis for public policy.

Recommendations

1. Research should be continued toward the goal of quantitative resource estimates including the use of regional metallogeny.
2. Because of the immediate need to upgrade the effectiveness of mineral resource assessments in public policy decisions, quantification should be considered in all cases where it is scientifically justifiable.

ISSUE 4: WHAT ARE THE MINIMUM REQUIREMENTS FOR METALLOGENIC ANALYSIS IN RESOURCE ASSESSMENT?

If an adequate metallogenic analysis does not already exist for the region surrounding an assessment study area, certain minimum resources are required to produce a metallogenic analysis: (1) information on regional geology (and tectonic interpretation), deposit models, regional geophysics, geochemistry, and remote sensing, and mineral occurrence information and (2) experts on regional geology and deposit models and geophysicists, geochemists, and remote sensing specialists.

Recommendations

The information identified above is best synthesized into metallogenic maps and reports, which should contain the following minimum items: (1) for maps, genetic types of deposits, sizes of deposits, commodities contained in deposits, regional metallotects, and geology (lithology, age, tectonic setting); and (2) for reports, geologic history and metallogeny, deposit types, history of exploration (discovery and production), discussion of metallotects, tables of deposits and characteristics, and potential for undiscovered resources.

DISCUSSION GROUP 2B

METALLOGENY AND MINERAL RESOURCE ASSESSMENT

By Thomas P. Miller and Kathleen Johnson
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SUMMARY

An understanding of the principles that comprise metallogeny and the continuing use of such principles enhance any mineral resource assessment and are indeed the philosophical foundation on which the most comprehensive assessments are based.

One of the most common uses of metallogenic principles is in association with conceptual models. Models are a powerful tool in mineral resource assessment but must be used with some caution because current data bases are inadequate for formulating many models. A thorough understanding of metallogenic principles, however, is the key to developing more usable models.

Metallogenic studies most directly impact resource appraisals in their early stages, when the question is asked, "What resources can be inferred in the study area from what is known about the geology of the study area and of adjacent regions?" Metallogenic principles are also used in synthesizing available information, determining what information is needed, outlining of tracts favorable or unfavorable for the occurrence of resources, updating previously prepared mineral resource assessments, and making mineral deposit models.

Research is needed in a variety of fields related to metallogeny, particularly the relation between metallogeny and topics such as plate tectonics and tectonostratigraphic terranes, metallogeny in time and space, and characterization of known metallogenic provinces. International cooperation is needed, so that important deposits having no known analogs in North America at present can be studied. Workshops similar to this one but focused on metallogeny should be encouraged.

INTRODUCTION

This discussion group took the position that the application of metallogenic principles, which probably dates back to society's first substantial use of mineral resources, is useful in making most mineral resource appraisals although we agreed that it is possible to make an assessment disregarding metallogeny. A mineral resource appraisal attempts to predict the mineral endowment of a tract of land whose boundaries may have been drawn with little regard for geology. To make such an appraisal, we must use a combination of what is known about the geology and resources of the tract and what we can predict on the basis of metallogenic principles developed elsewhere.

For our own purposes, the definition of metallogeny provided by the American Geological Institute's Glossary of Geology was deemed adequate, although we noted that different interpretations are possible and even likely. Metallogeny is "the study of the genesis of mineral deposits, with emphasis on their relationship, in space and time, to regional petrographic and tectonic features of the earth's crust."

The discussion thus turned to the ways in which we use metallogeny, the information required to enhance our application of metallogenic principles, and the limitations of metallogenic theory as applied to mineral resource appraisal. A related issue is whether the application of metallogeny to mineral resource appraisals is necessarily dependent on mineral deposit models. Four specific topics addressed were: (1) how metallogenesis should be used in resource assessment, (2) how mineral deposit models should be used in metallogeny to prepare a mineral resource assessment, (3) in areas where the geologic data base is limited, what role the application of metallogenic principles can play in making a mineral resource appraisal and what additional information can be used to enhance our understanding of the metallogeny, and (4) what directions research in metallogenesis should take.

TOPIC 1: HOW SHOULD METALLOGENESIS BE USED IN RESOURCE ASSESSMENT?

It was unanimously agreed that metallogenic principles and studies are an integral and important part of mineral resource appraisals. However, the precise manner in which metallogenesis is applied to resource appraisals is not so clear and varies among areas. In general, we recognize the following method of application.

Metallogenic studies most directly impact resource appraisals in the early stages, when the question is asked, "What resources can be inferred in the study area from what is known about the geology of the study area and of adjacent regions?" At this level, most information comes from knowledge of deposits, lithotectonic zones, and geophysical and geochemical patterns in the area under consideration. The ideas generated at this stage of a metallogenic study guide the next phases of the mineral resource assessment, including geologic mapping, sampling, and model development. If future work is not possible (because of constraints of time and (or) funding), then these metallogenic studies provide the central information for the resource assessment.

If future work is possible, the application of metallogenic principles continues concurrently and involves comparisons with increasingly larger metallogenic models. The end result is consideration of the potential for all deposit types known to occur in analogous metallogenic belts. The completed metallogenic studies are integrated in the final mineral resource assessment.

Metallogenic principles are also used in synthesizing available information, determining what information must be added, outlining tracts favorable or unfavorable for the occurrence of resources, updating previously prepared mineral resource assessments, and making of mineral deposit models. On occasion, metallogenic principles can be used in selecting areas for mineral resource assessment, as the Alaska Mineral Resource Assessment Program and the Conterminous United States Mineral Assessment Program have done.

TOPIC 2: HOW SHOULD MINERAL DEPOSIT MODELS BE USED IN METALLOGENY TO PREPARE A MINERAL RESOURCE ASSESSMENT?

We defined a model (of one deposit type) as representing a systematic array of pertinent information characterizing that deposit type and distinguishing it from other deposit types. We recognized the value of conceptual models in metallogeny, particularly as guides to thinking and as benchmarks against which other deposits can be compared, but we are concerned about possible overdependence on models.

Models are used to characterize geologic environments favorable for the occurrence of mineral deposits and, alternatively, to highlight the mineral commodities to be expected within a particular area, to make and (or) revise metallogenic maps, to suggest processes that may have formed the mineral deposits, to extrapolate qualitatively and (or) quantitatively from the known to the unknown (that is, from areas having enough data to areas having little data), and to test hypotheses concerning the origin of mineral deposits.

The problems of using models in metallogeny and mineral resource assessment can be significant, however, and we have identified several.

Nonconventional Mineral Deposits

Nonconventional mineral deposits fit no presently formulated model. In theory, all mineral deposits can ultimately be assigned to a model. But, if our approach to mineral resource assessment is dominated too strongly by the application of models, we run a high risk of missing those "unconventional" deposits whose model type has not yet been identified. This persistent concern was expressed repeatedly in one form or another during the group's discussion.

Extrapolation of Models

The extrapolation of mineral deposit models from one area to another introduces different degrees of uncertainty into metallogenic studies and mineral resource assessments. The uncertainty increases and becomes difficult to measure as attempts are made to quantify a resource assessment.

Definition of Model Parameters

We lack detailed information on the critical parameters that ultimately define the models for many deposit types. As a result, we run the risk of having the mineral resource assessment unduly influenced by an apparent "poor" fit of data to the preconceived model.

TOPIC 3: WHAT ROLE CAN METALLOGENIC PRINCIPLES PLAY IN MAKING A MINERAL RESOURCE APPRAISAL IN AREAS HAVING LIMITED DATA AND WHAT ADDITIONAL INFORMATION CAN BE USED TO ENHANCE OUR UNDERSTANDING OF METALLOGENY?

This topic was selected to illustrate a more specific need and use of metallogenic principles in resource assessment. Because areas where bedrock exposure is limited or where geologic study has been limited by inaccessibility or other factors are particularly dependent on the application of metallogenic principles in mineral resource assessment, assessments of such regions must be based largely on metallogenic principles. Metallogenic concepts are necessary in designing geophysical and geochemical surveys to acquire and interpret new data. In areas where it is not possible to acquire new information, metallogenic principles provide the framework for interpreting existing geoscientific data. Examples include resource assessments carried out in areas of glacial cover, in areas such as the midcontinent where assessments of the basement rocks are desired, and in developing nations having limited geologic data bases.

TOPIC 4: DIRECTIONS FOR RESEARCH IN METALLOGENY

Although metallogenic principles can be usefully applied to mineral resource appraisals, many topics within the field of metallogeny remain to be studied. Many are broad questions whose resolutions bear on the credibility of the predictions that we make. The first need that we identified is continuing synthesis of existing geologic and mineral occurrence data to produce metallogenic maps at a variety of scales, including global, continental, and regional. These syntheses will ultimately address a variety of topics, including but not limited to the relation between metallogenic processes and plate tectonics and tectonostratigraphic terranes.

Another area for research is metallogenic evolution with time and space. Examples of problems in this area include (1) variations in metallogenic provinces through time, (2) variability of deposit types within and possibly across geologic trends of otherwise coherent packages of rocks, and (3) differences between mineral deposits in apparently similar packages of rocks.

A concerted collaborative effort with industry and other governmental agencies should be focused on the reliability of timely descriptions of all significant deposits, especially including the "one-of-a-kind" type that may occur outside North America. With respect to mineral resource assessments, evolving metallogenic concepts must be applied to update earlier assessments.

Traditionally, metallogenic provinces have been defined by recognizing metallogenically related deposits and drawing boundaries around them. To improve our ability to define such provinces adequately, however, we must undertake projects whose goal is characterization of the geophysical and geochemical signatures of known metallogenic provinces. A related problem is determining the influence (if any) of the geochemical cycle of selected elements on the distribution and extent of metallogenic provinces. Finally, we see an immediate need to research the application of digital technology to the production and updating of metallogenic maps and mineral resource appraisals. This research will necessarily involve a rigorous understanding of metallogenic principles as well as of the capabilities of computers, digitizers, plotters, and similar equipment.

DISCUSSION GROUP 3

DEPOSIT TYPE MODELS: A QUANTITATIVE BASE FOR RESOURCE ASSESSMENT

By Byron R. Berger[1] and Charles W. Jefferson[2]

SUMMARY

A minimum subset of attributes must be defined for a mineral deposit model to be considered complete. These attributes should be classified as either essential (must be present for the deposit to qualify as the type under consideration) or accessory (present in many deposits of a type but not known to be empirically or genetically fundamental to the assignment of that type). These attributes should be quantified as to the frequency of occurrence within examples of the type and also weighted as to their degree of importance.

Submarginal and noneconomic mineral deposits should receive further study. They can teach us much about the processes and systems responsible for world-class deposits of the same type.

Grade-tonnage and probability-of-occurrence models may not be effective in any but the largest lithotectonic domains. They cannot be meaningfully applied to small, isolated tracts.

Semiquantitative estimates can be made of the desirability of different terranes for exploration at some time in the future. Geologists should not attempt to foresee future technological and economic developments or changes in governmental regulations, all of which contribute to the determination of the value of potential deposits.

INTRODUCTION

Synoptic descriptions of mineral deposit types are used to predict the probabilities of mineral deposits using fragmentary data from geologic domains. In addition, the development of these deposit type models helps to identify important problems that remain to be solved. Education and better communication are byproducts of model development.

This summary presents the views of the discussion group on selected issues regarding mineral deposit type models. The major issues discussed are (1) the kinds of data that should be included in a deposit type model (fig. 1), (2) quantitative derivation of models, (3) different ways of classifying deposit types and quantifying deposit type attributes, (4) mechanisms for publishing and modifying synoptic descriptions of deposit types, and (5) quantitative applications of models to selected regions.

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DISCUSSION

Necessary Data for Deposit Type Model

Before a system of models can be constructed, it is important to define the data needed as a base common to all deposit types. Figure 1 is a listing of recommended attributes. These attributes can be used descriptively, or they can be quantifiable.

Quantitative Derivation of Models

To use ore deposit models as tools in quantitative resource assessments, it is essential to derive the models in a systematic manner. Features composing any given deposit should be quantified as to (1) frequency of occurrence (such as the proportion of a given attribute within a type), (2) magnitude, (3) spatial distribution within or about the deposit, and (4) zoning. The selection of the specific deposits that make up a deposit type is determined by statistical evaluation of empirical observations and an understanding of processes. The frequency and distribution of these observations and processes determine the essential and accesory attributes of the deposit type. An essential attribute is one that must be present for the deposit to qualify for the type under consideration. An accesory attribute may be present in a number of deposits of a type but is not known to be empirically or genetically fundamental to the assignment of that type. As understanding of an accessory attribute increases, it may become an essential characteristic.

The terms essential and accessory are preferred over other terms such as diagnostic, permissive, and indicative, because they are derived from standard petrographic nomenclature and are ideal for describing mineralized rock types. The latter terms can be used by scientists in applying deposit types to quantitative resource assessment but not in building deposit type models. Essential and accessory attributes should be weighted for each individual deposit type model, but the weights need not be identical from model to model.

Many features are quantified in one way to determine the existence of or inclusion of a given mineral occurrence within a particular type but are quantified in a different way to apply that deposit type to resource assessment. When the applicability of a model is tested, the number of essential and accessory attributes for that type should be recorded as well as the number of times that these sets of attributes are observed within the study area. Ways should be found to estimate the degree of confidence in the certainty of fit to the deposit type model used.

Classification and Quantification

The descriptive format given in figure 1 is the first step in classifying deposit types from the data pool. Any method of grouping individual deposit types into a classification scheme must (1) be robust and adaptable to additions of new deposit types and changed genetic concepts or understanding; (2) provide predictability (that is, help predict mineral deposit occurrences from fragmentary data); (3) communicate quantitative and qualitative information to a variety of users viewing the deposit type concept from different aspects (for example, commodities, large to small mineral assessment tracts, and so on); (4) identify significant unresolved problems; and (5) be based on essential attributes of studied deposits.

These requirements seem to be best served by an hierarchical scheme having at least three levels of classification: (1) geologic environment and mineralizing process(es); (2) subsets of the geologic environment (specific rock types) and subsets of attendant processes (specific parts of geochemical systems, possibly including commodities) at the district level of data; and (3) essential and accessory attributes,

- NAME OF DEPOSIT TYPE: The most noteworthy geologic characteristic of a deposit type including commodity; well-known example when desirable.
- ALTERNATE OR COMMON NAMES
- PRINCIPAL ECONOMIC COMMODITIES
- BYPRODUCTS
- EXAMPLES OF TYPE: ASSOCIATED DEPOSIT TYPES
- SYNOPSIS: A brief summary, including the form of the deposit
- ECONOMIC ASPECTS: Worldwide frequency of occurrence, grade and tonnage, probability of occurrence, density or clustering in districts, importance; includes reserves and resources.
- REGIONAL GEOLOGIC FRAMEWORK: General geology, summary of historical geology, geomorphology, tectonic-tectonostratigraphic settings, structure, depositional environments, geochemistry, geophysics, paleohydrology, metamorphism, and later thermal events.
- AGE: Country rock
    - Immediate host rock
    - Mineralized rock
- GEOLOGIC SETTING OF DISTRICT:
    - Host rocks (composition, textures, mineralogy, and so on).
    - Associated rocks (composition, textures, mineralogy, and so on).
    - Local structural geology
    - Geochemistry, geophysics
    - Frequency of occurrence of mineralized rocks: space-time plots; density, clustering, linear arrays; probability of occurrence.
    - Paleohydrology
    - Metamorphism and later thermal events
- DEPOSIT ATTRIBUTES:
    - Mineralogy (including alteration, mode of occurrence, zoning).
    - Textures
    - Geochemistry (majors, minors, trace) and zoning
    - Isotope geochemistry and zoning
    - Fluid inclusion, geochemistry, and zoning
    - Structural-stratigraphic controls
    - Weathering effects, metamorphism, and later thermal effects
    - Metamorphism
    - Later thermal events
- COMMENTS ON GENESIS
- SIGNIFICANT UNRESOLVED PROBLEMS
- ORE CONTROLS-GUIDES TO EXPLORATION
- SKETCH
- REFERENCES

FIGURE 1.--Data recommended for the development of deposit models.

including commodity at the district and mineralized rock levels of data. These levels are the only ones quantitative enough for application to resource assessment.

Any classification scheme should include computer-based cross-referencing files of the attributes in the deposit type models. These files would provide indices to the essential characteristics of deposit types, which would remind an assessor considering a specific geologic environment of the types of deposits possible in that kind of environment. They would also remind an explorationist of the other types of deposits and commodities to be suspected in a particular environment being explored.

The number of deposit types is dependent on the level of knowledge that exists. The number of deposit models may depend on attributes useful in recognizing a deposit type or the tools needed in the exploration process. Similarly, the limited but rapidly expanding data base is still insufficient to tell us whether known mineral deposit types are representative of the whole spectrum of mineral occurrences. We recommend that greater attempts be made to acquire data for submarginal deposits because of what they may tell about processes and systems responsible for world-class deposits of the same type.

Complex multiple-process deposits that occur in composite lithotectonic terranes pose special problems in classification and quantification. Grade-commodity-tonnage models appropriate for a general deposit type in one terrane may not be applicable to a similar deposit type in another terrane. Similarly, the interpretation of a tectonostratigraphic terrane characteristics of a particular deposit type may change. This change in interpretation of an essential feature necessarily changes the assessment implications for that deposit type.

Publishing and Modifying Descriptions of Deposit Types

A forum for the publication and discussion of models is desirable. Peer review should be used to decide which models will be revised or replaced, a step that will normally occur when scientific understanding has progressed sufficiently. Alternative interpretations for the same deposits, included in the same deposit type descriptions, should be resolved by the same process. The time is ripe for active publication of review articles which include one-page deposit type summaries using formats like that in figure 1. One such series has already been started in Geoscience Canada. Other possible avenues of publication include scientific communications in Economic Geology or governmental agency open-file publications.

Quantitative Applications of Models

Major uncertainty attends any attempt to derive quantitative resource estimates of assessment lands. Grade-tonnage and probability-of-occurrence models might not be effective in any but the largest lithotectonic domains and appear to be less meaningful in isolated small tracts.

Semiquantitative estimates of the desirability of different terranes for future exploration can be made. Deposit models can be used to assign numerical scores to each geologic domain on the basis of the numbers of essential attributes present for a number of deposit types. Geologic domains can then be rated either absolutely or relatively as to the likelihood that explorationists will want to explore, trench, drill, or build roads under favorable economic conditions. Expert economists can provide some indication of when such favorable economic conditions might apply.

Economic geologists cannot evaluate future technology, economic conditions, or government regulations when deciding how to deal with mining factors such as stripping ratios, dips of veins or beds, or susceptibility of mineralized rock for in situ mining. The history of exploration and mining is replete with examples of deposits that languished for tens of years before the proper technology or uses were obtained to make possible their economic exploitation; many giants still await development.

DISCUSSION GROUP 5

THE MANAGEMENT OF MINERALS INFORMATION AS RELATED TO RESOURCE ASSESSMENTS

By Jack Garnett[1] and R. F. J. Scoates[2]

SUMMARY

Discussion group participants agreed that consideration of the special requirements of current and potential user groups has been insufficient in past mineral resource assessment (MRA) studies. As a result of this discussion, a list of current and potential client groups was made, and it became evident that the output formats of MRA reports must be tailored to effectively meet the requirements of these client groups. Traditional MRA reports, which still constitute the basic document, should be supplemented by a series of condensed summaries addressing the special requirements of diverse client groups and prepared by technical editors. The group agreed that basic data sets pertinent to resource assessment reports should be maintained and upgraded for potential future reappraisals and other types of studies. Discussion of assessment procedures identified the vital need for field studies that provide "ground truth" for attaining required confidence levels for credible assessment statements. Continuing enhancement of machine-based data sets and their compilation and integration are essential to assessment studies.

INTRODUCTION

The basic premise that guided our discussion was that the variety of clients either requiring or potentially interested in MRA's could not be universally satisfied by the production of one final report, no matter how careful its design.

The client population was then separated into five general categories:

1. Government mineral agencies comprising State, Provincial, Territorial, and Federal geoscience professionals.
2. Mineral industry exploration and mining professionals.
3. External mineral-impacting governmental agencies (for example, U.S. Bureau of Land Management, U.S. Forest Service, environmental agencies, municipal government agencies, and congressional and other government political interface personnel). Within this category, MRA information must be designed for distribution to both nongeologic, scientifically trained professionals and nonscientific senior management and policy advisors.
4. Ecologically motivated citizen advocacy groups, generally involving nongeologic, scientifically trained personnel.

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5. The "general public," a broad-based category in which two main components were specifically designated (namely, citizens directly affected geographically by potential mineral resource impacts and general educational institutions interested in MRA documents designed to raise public awareness).

DISCUSSION

It has been assumed that, in general, a MRA generates a single, technically written final reports. The comprehensive, scientifically based synthesis of available data sets used in arriving at such a report has been accepted as a reasonable process for producing a main working document from which a number of subset, client-specific reports can be extracted. The full document and its accompanying retrievable raw data files will, with some unspecified reservations, satisfy the first two client groups listed above. The last three groups require condensations designed specifically to meet their specialized audience requirements.

If interaction between these five indifferently related groups is to be improved, a new sort of "interface specialist," ideally trained in both science and communications, must be created to condense the substance of a comprehensive document into a succinct "image" document. Initiating agencies must accept such transformations as a constructive technical edit rather than as a distortion of scientific integrity.

Output Formats

General categories of output formats resulting from MRA studies were identified as basic data sets, comprehensive syntheses, condensed summaries, and computer data processing.

Basic Data Sets

Basic data sets represent the complete package of geoscience input necessary for MRA studies. Fundamental to these data sets is the geologic framework generated by existing surveys and fieldwork "ground truth" examinations. Additional noninterpretive data available, such as systematic geophysical, geochemical, mineral inventory and remote sensing data may also form an integral part of the data set. All such data must be available in publishable form. In addition, all background data should exist in readily retrievable machine-processible files. Such files would serve not only as an archival source but would also be continuously upgraded as new data become available.

Comprehensive Syntheses

Comprehensive syntheses involve combinings basic data sets to construct the overall geologic framework essential to the mineral resource appraisal process. Evaluations of metallogenic aspects are integrated with all available basic data sets and compared with deposit descriptions and models. The interpretive part of this report culminates in a final assessment matrix. No conclusions were reached regarding the merits of various methods of qualitative and (or) quantitative assessments.

Condensed Summaries

It is evident that the basic data and comprehensive syntheses formats, which represent the single document approaches of many MRA statements, have not satisfied the needs of all identified client groups. For this reason, a third output format has been identified to specifically address previously unsatisfied client needs.

A number of condensed summaries could be produced for each full MRA document. These summaries, which would also be published documents, could range from one-page executive summaries to very short publications highlighting technical data, syntheses, pertinent interpretations, and conclusions that deal directly with identified client needs. Consideration should be given to other media presentations such as short video productions, poster sessions, lectures, and so on.

Computer Data Processing

A number of on-line machine-based data sets were outlined. The value that such files could contribute to MRA was not disputed, but a number of current developmental problems suggest that the present generation of these systems was underused and not sufficiently user friendly.

Problems specified included lack of attention to determining specific user needs that can be satisfied by machine-based analytical files; lack of compatibility between baseline data systems, which inhibits efficient resource overlap; and lack of communication between generators of scientific data and computer programmers. Machine-based compilation and integration of complementary information sets are clearly desirable goals. This capability should be available directly to the scientist as needed for research and evaluation. Although progress toward this ideal depends on the evolution of natural language interface systems, one desirable contribution at this stage would be the emergence of computer-sophisticated geologists who could bridge the gap between geology and the computer sciences.

Because these fields are so new, it is difficult to attract qualified staff and still maintain the necessary level of geoscience expertise. It was, however, strongly emphasized that organizations acquiring machine capability must also acquire adequate and well-qualified support staff, particularly for developing scientifically credible data management systems.

RECOMMENDATIONS

To be more universally effective, MRA's must be designed to produce a number of compatible but separate client-specific reports.

Reports and presentations directed at both the nongeologic scientific audience and the nonscientific management-policy-public audience should be extracted from the original all-inclusive technical document by interface specialists trained in both science and communications techniques.

Regardless of the variety of synthesized output formats generated, the baseline data sets must also be made available in readily retrievable (ideally) machine-based files.

The basic foundation for a credible MRA must be a geologic map derived from ground-confirmed investigations. Where no map exists, no amount of additional information set enhancement can raise the confidence level to a scientifically acceptable status.

Accelerated development of compatible machine-based data sets is essential for a more effective resource assessment framework. Such file development must be accompanied by simultaneous establishment of geologically trained support staff, particularly in the area where geology and the computer sciences interface area. University geoscience departments should be encouraged to develop integrated programs to satisfy this requirement.

MRA's must be clearly labeled as time-dependent information-constrained documents. Their design should accommodate the efficient periodic updating that will be done as a matter of policy.

DISCUSSION GROUP 7

RECOMMENDATIONS FOR RESEARCH IN DETERMINING THE PROBABILITY OF MINERAL OCCURRENCE

By Gordon P. Eaton[1] and Robert G. Garrett[2]

SUMMARY

Discussions by workshop participants led to two sets of recommendations: (1) recommendations of a broad nature concerning the implementation of studies involving the probability of mineral occurrence and (2) certain specific recommendations for future research studies relevant to the probability of mineral occurrence.

General recommendations were:

1. To develop an atlas of "areas of analogous geology" for mineral deposit types, based on and patterned after the existing atlas of mineral deposit models. These areas of analogous geology should include probability-of-occurrence models. To meet this objective, formal rules must be developed for defining the boundaries of areas of analogous geology by deposit type. Steps should be taken to assure wide use of these atlases in project practice.
2. To develop controlled test-area techniques for evaluating the validity of the application of different resource assessment procedures, including both subjective probability and quantitative numeric methods, in contrasting geologic terranes.
3. To undertake retrospective statistical evaluations of the effectiveness of individual measurement techniques and observations currently in use in environments hosting differing mineral deposit types, the objective being to judge both the technical suitability and the cost effectiveness of various procedures. Eventually, such information should be made available as an appendix to an atlas of mineral deposit models.
4. To develop the means to ensure continuous interaction among the practitioners of all disciplines in resource probability modeling at all stages of assessment. Specifically, after the geology of an area to be assessed has been reviewed, a list of expected mineral deposit types should be prepared. An evaluation of the expected geologic, geochemical, and geophysical signatures of those types should then be made and appropriate data gathering planned. For time-constrained projects, this process may occur only once; for longer projects, it should be iterative.

Operational recommendations were:

1. To develop procedures for the continuous review of multivariate methods in light of geologic knowledge to improve both subjective and objective numeric assessment methods.
2. To investigate the spatial distribution of individual mineral deposit types in well-explored areas (the reference areas of analogous geology), as both point and line processes.

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3. To develop formal rules for defining areas of analogous geology for different mineral deposit types.
4. To determine the most appropriate distribution functions for subjective probability estimates.
5. To assess various alternative methods for estimating the marginal probability that "no deposits" will occur.
6. To develop and critically examine rules and methods for combining diverse kinds of geoscience data, specifically emphasizing linkages through mineral deposit models.
7. To develop and evaluate alternatives to the approach of estimating numbers of discrete deposits, especially where specific types of mineral deposits create difficulties for that approach.

INTRODUCTION

Estimating the probability of occurrence of mineral deposit on public lands has become an important issue recently for two reasons. First, a mechansm for estimating these probabilities is required to provide fundamental input for the economic modeling that will guide the decisions of Federal land use managers, policymakers, and minerals analysts. Second, estimating these occurrence probabilities contributes to the development of a predictive economic geology. To achieve this end, strong interaction is needed between the traditional principles of economic geology and the systematic application of quantitative methods. This interaction is essential because of the complexities of the entire process, which ranges from which models to apply to what data need to be collected.

At present, the quantitative assessment of mineral deposit occurrence probabilities, together with deposit type grade-tonnage distributions, appears to be the best means available to compare directly the value of mineral resources with values derived for other competing land uses. Probability-of-occurrence estimates, insofar as possible, should be consistent with the available mineral deposit models to take advantage of the large volume of data that has been assembled in the form of grade-tonnage models. It is anticipated that both subjective probability and traditional statistical estimation techniques will be developed and tested. It would be advantageous if the marginal probability that "no deposits" will occur could be assessed and explicitly stated, either subjectively or with the aid of some numeric procedure.

CRITIQUE

Thus far, a variety of observations and techniques has been brought to bear in preparing mineral resource assessments. Some are of a geologic, geochemical, or geophysical nature, some have their bases in statistical theory, and others are designed to provide the means of combining different kinds of data in ways that will optimize their collective usefulness. The science of assessment has moved forward from simple identification of areas or regions that may be favorable for mineral occurrence to identification of specific mineral deposit types, together with their probable grades and tonnages, that may be present in an area to, finally, estimation of the probable number of such deposits with in that area. These developments have escalated the need to improve both the objectivity and the validity of the assessments.

Generally, the tight, deadline-driven schedules of resource assessment activities by governmental agencies and limited budgets have made it difficult to conduct a comprehensive review and judgement of the work itself, something that sound scientific practice suggests should be done from time to time. There is a need to develop the means to test or check both the validity of the resource assessments that have been made to date and the relevance and cost effectiveness of the techniques (or combinations of techniques) that have been brought to bear on the problem. If the process is to be improved and optimized, there is a need to pause periodically and evaluate the progress that has been made. Whether the individual techniques or methods currently being used are valid must be determined by tests performed on the data and resource assessments made thus far. If certain techniques or observations are found to be less effective and, particularly, less cost effective than others, funds can and should be shifted to what are judged to be more relevant procedures.

GENERAL PROCEDURE

Ideally, geologists begin by identifying which deposit types are most likely to be present in a given area. This identification is followed by selection of specific geochemical, geophysical, and other techniques regarded as optimally diagnostic for given deposit types. The resource assessment process should incorporate deposit type identification at an early stage to ensure that only those techniques useful for a specific deposit type or types are used. Deposit types thus must be described in greater detail, and models must include the probabilities that any given diagnostic and (or) permissive features will occur. To the extent possible, descriptions should be quantitative (giving, for example, the median and range of deposit geometries and the size of alteration haloes). Those features usually thought to be associated with ore deposits should be identified and quantified in control areas where no deposits are known. Geologists who conduct resource assessments thus need to first identify the deposit types that may reasonably be expected to occur in a region on the basis of an initial geologic review and then follow up with a more detailed investigation of the geology of the assigned area.

DISCUSSION

Research into the methodology for determining the probability of occurrence of mineral deposits in a prospective region has led to a focus on the "number of deposits" as a key unknown that must be estimated. If this estimate is made and grade-tonnage curves are constructed for the different mineral deposit types judged to be present in a region, estimates can be made of the resources available and confidence bounds determined for them.

Such an approach requires three elements: (1) the recognition of regions analogous to those defined by the available mineral deposit models; (2) the development of predictive models for numbers of deposits in well-explored areas for those mineral deposit types; and (3) the application of these models, along with site-specific geoscience data from the prospective region, to produce estimates.

A number of outstanding problems associated with this procedure require study if we are to improve our ability to carry out resource assessments by means of the "play-prospect" methodology, which has proven useful in the study of oil and gas resources.

In certain classes of deposits, the selection of the cutoff grade affects the perceptions of the geometry, particularly the discreteness of individual deposits. These deposits are typically those in which a body of rock contains zones of higher grade "ore" surrounded by a large, continuous body of lower grade material, like "plums in a pudding." If low cutoff grades are selected, the determination of the number of deposits may be unmeaningful or difficult at best, if quantitative models are based on the "plums" rather than on the "pudding." Where such deposit types exist, assessments of resources might do well to use methods other than estimating numbers of deposits.

In estimating the number of deposits in a region, simple models based on the number of deposits per unit area in well-explored regions or on the proportion of an area containing mineralization have been investigated or used for extrapolation. The extrapolation method has been used in sedimentary basins where the "ore " situation, although complicated, is still simpler than that found in igneous, volcanic, and metamorphic terranes.

For regions of complex geology, other procedures may well prove more effective, even at the cost of greater complexity. It is necessary to recognize areas of analogous geology on the basis of geologic rules (for example, regional geologic and ore control criteria, which should be considered a part of mineral deposit models). A simple example would be podiform chromite deposits that occur within dunites in the harzburgite (cumulate or tectonite) zones of ophiolites. As an alternative to this purely geologic procedure, which in some cases could include a large subjective component, areas of analogous geology might be defined with the aid of multivariate statistical analysis or image (map) analysis systems. The advantage of the former method is its explicit consideration of geologic theory, whereas the latter may be advantageous because it is not explicitly based on geologic theory and may uncover unexpected relations. Interaction between these two approaches is essential, because geologic theory may have overlooked useful relations, and, alternatively, the multivariate methods may produce artifacts based solely on limited data or faulty model assumptions.

The multivariate quantitative approach uses a variety of pattern recognition methods. Examples are various regression, discrimination, and classification procedures. Perhaps logistic regression methods of discriminant analysis and correspondence or log-linear analyses hold the most promise. Logistic regression methods are relatively free from assumptions concerning properties of the data, and correspondence or log-linear analyses can be used with presence-absence binary data. Together with such methods, recent technological developments involving the processing of images and spatial data have made it readily possible to combine various types of geoscience data to produce interpretive spatial summaries (that is, the identification of prospective or favorable regions (areas of analogous geology) for resource assessment use). However, particularly with the multivariate statistical methods, care must be taken not to develop statistical models that pool across different mineral deposit models. Such procedures can lead to the mutual cancellation or blurring of useful relations in the data, and the practice is contrary to today's operational approach, which stresses disaggregation by mineral deposit types.

One reason for the relatively limited use of multivariate methods may be the major commitments of time and resources required to prepare consistent multidisciplinary digital geoscience data bases as compared with the limited benefits that have accrued from their use in some instances.

A topic of major concern in multivariate method applications is the extent to which different data types can be combined. Individual geoscience data bases may contain data of widely differing natures, ranging from potential field measurements (for example, gravity and magnetics) to discrete point location types (for example, geochemical data and remotely sensed pixels). Moreover, the scale of these data may vary enormously, from gravity data collected at one site per 10 km^2 to remotely sensed pixels at 40,000 per km^2, a contrast of almost half a million. Between these data density extremes lies a whole range of geochemical and geophysical parameters. In addition, not all these data are acquired with equal precision and therefore should not necessarily be relied upon equally.

Combining differing data types in single analyses requires study, as do the rules and logical operations governing such combinatorial tasks when it is appropriate to undertake them. For example, when and how can one add or otherwise mathematically or logically operate on airborne magnetic, geochemical, and remotely sensed data to combine them into a single map? The question arises as to whether it would be more effective and appropriate to study data of disparate types separately and then have experts combine the resulting interpretive information, perhaps with the aid of image analysis systems.

When pattern recognition is used in selecting areas of analogous geology, there must be a constant interplay between subjective geologic appraisal and quantitative numeric methods in order to improve the quality of both procedures and to select the most appropriate cutoff values in the statistical estimators for reflecting the boundary between prospective and favorable areas and less favorable areas. One useful parameter would be a conditional probability indicating the degree of belief in the proposal that an area of analogous geology does not in fact contain any deposits of the model type under consideration.

Once prospective or favorable areas of analogous geology have been identified, estimators for number of deposits present in an area need to be developed. The simplest approach would be to form histograms for the number of deposits per unit area for specified well-explored regions containing the deposit model under study. A more sophisticated approach would be to relate number of deposits per unit area to geologic features through regression models. Poisson regression models may hold particular potential.

Subjective procedures for estimating number of deposits have been used extensively, in which geologists and resource analysts subjectively estimate the number of deposits of a specific model type in an area of analogous geology. The result may be as simple as a single-figure expectation, or it may include a statement involving a measure of the degree of belief (for example, a 1 in 10 belief that at least one deposit occurs and a similar belief that no more than four deposits may occur). A topic for study is the underlying frequency distribution of such subjective estimates and the most appropriate statistical model to represent them (for example, normal, exponential, Cauchy, log normal, and so on). As models improve, subjective estimates could be more meaningfully combined and used in resource estimation.

The spatial distribution of mineral deposits is still not well understood. In the past, deposits have been represented by points or lines on maps, and certain patterns of clustering have often been observed, depending on the mineral deposit type. For example, the negative binomial distribution has been demonstrated to better fit the number of deposits per unit area than the Poisson distribution, the inference being that the mineral deposits are not formed by purely random processes. The Poisson distribution, on the other hand, provides a better model for the distribution of mineral districts in large regions, a suggestion that at least some random component is present in nature. Understanding the patterns of spatial distribution is an important step toward quantitative resource assessment. Clustered patterns may be better explained by compound distributions. These stochastic point processes may lead to a better understanding of the genetic factors controlling deposit formation as well as provide a useful tool in resource assessment. The distribution of mineral deposits in well-explored regions remains an ongoing research topic.

CONCLUSION

Armed with delineated areas of analogous geology for different deposit model types and estimates of the numbers of each deposit type present, an assessment can proceed. However, continuous critical appraisal of the data and methodology is essential; subjective geologic appraisal must be played against quantitative numerical procedures. Additionally, if data from a favorable area suggest that more (or less) abundant mineralization than the original deposit model control area had indicated, the geologist undertaking the assessment may wish to modify his estimates to make them consistent with the available geoscience observations. In any event, analysts and geologists must use their professional judgement regarding the appropriateness of the analogies to the deposit model control area.

CONCLUSIONS AND CRITIQUES

WHY MINERAL DEPOSIT MODELS CAME TO BE USED IN REGIONAL ASSESSMENTS

By A. T. Ovenshine
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ABSTRACT

Two types of models are commonly used in regional assessments of metallic mineral resources. Tonnage and grade models are used primarily to increase communication with the policy community that asks for assessments because they provide a measure of the magnitude and quality of undiscovered deposits. Descriptive exploration models are used to meet the needs of the scientists themselves. Using exploration models simplifies the assessment process, improves the reproducibility of results, and ensures that the insights derived from years of basic research on mineral deposits are brought to bear on the problem of reliable regional mineral resource assessments.

THE REGIONAL ASSESSMENT MISSION

The U.S. Geological Survey (USGS) began to use models in regional assessments 21 years ago, when the 1964 Wilderness Act instructed us to determine the mineral values of wilderness areas. I think that Congress's reasoning in ordering these studies was to learn what minerals were in the wilderness as a precaution against the day when a national emergency might make their mining necessary. In 1964, the mines, smelters, and foundries of America were still producing profits and jobs, and Congress saw metals as important to our national well-being.

The requirement for mineral surveys was repeated in some subsequent land acts and understood to apply to many others. As time went by, however, the original purpose of the studies--a hedge against disaster--changed to the provision of technical opinions to those making land use plans and decisions. Our results were presented in reports that we expected would be used by land planners, policymakers, Congressmen, and Senators. In time, we came to call these studies "resource assessments" or "resource appraisals."

This abbreviated history is for a point: geologists began making resource assessments because society wanted them, not because we saw them as the logical next step in advancing Earth science. Moreover, we were poorly prepared to make resource assessments. There was not much of a foundation of basic research to draw on, and some of the reasoning and much of the data that were needed belonged to mining companies, which sometimes guarded them jealously.

By the late 1960's, we had surveyed enough areas and published enough reports to begin getting reviews of our work. Much to our surprise, we were panned. The main complaints concerned the technical language that we used and the lack of explicit statements of mineral value. Our critics may have had a point; although the paragraph that follows is an outrageous invention, it represents the general way in which we presented some of our early "determinations of mineral value":

> The Jurassic(?) andesitic to dacitic volcanic rocks--especially the breccia phases--locally exhibit trace amounts of base and precious metals, particularly in areas where they unconformably underlie arkose of Miocene age and are near porphyritic quartz monzonite stocks of Tertiary(?) age. Therefore, it is not possible to conclude that the wilderness study area is not mineralized to some degree, although the potential for development of economically viable mines cannot be determined without further study.

Through questioning, we learned what our critics wanted to find in our studies: simple, nontechnical statements about the type, location, quantity, and quality of mineral deposits in wilderness areas. Since we did not know how to accomplish this goal, short of drilling on closely spaced centers, we had a problem.

TONNAGE AND GRADE MODELS

By the mid-1970's, the USGS had a group working on the puzzle. Donald Singer was probably the first to see a path through the maze, but, doubtless, there were contributions and encouragement from Dennis Cox, Allen Clark, Richard Sheldon, Lawrence Drew, Donald Richter, and many others. Singer, who had more training in statistics and mathematics than most geologists, realized that frequency distributions of tonnage and grade for a kindred set of deposits could provide some of the information that our audience wanted about undiscovered deposits. I think that the first application of his method was in Donald Richter's work in Alaska's Nabesna quadrangle (Richter and others, 1975). For the first time, we mapped areas of potential for specific deposit types and estimated the numbers of deposits and quantities of metal that they contained at 10-, 50-, and 90-percent probability levels. The crispness of our statements was thereby vastly improved, but our results were still not as straightforward as the lay policymaker wanted. Grasping the concept of probability was undoubtedly difficult.

While Singer and his colleagues were grappling with the problem of describing undiscovered deposits, other economic geologists in the USGS began to worry about the scientific morality of what the resource assessors were doing.

By providing descriptions of resources that had not been pinpointed, sampled, and assayed, they felt that the resource assessors were making unsupported statements. And, the ethic of science does not welcome unsupported statements.

For several years after 1975, there was heated debate over land assessment using grade and tonnage models. Part of the controversy arose because the resource assessors allegedly paid too little attention to the geologic details of the deposits that they considered kindred and whose properties they aggregated to build tonnage and grade models. The histograms, their critics said, might well have included data from the geologic equivalents of apples, oranges, lemons, and bananas. But another part of the problem was that the critics did not listen to the orders that society issued. When they finally understood that regional assessments had to be made—and admitted that they had no better method to propose--the tensions of disagreement began to ease.

DESCRIPTIVE EXPLORATION MODELS

By 1978, a number of us simultaneously saw that we could greatly increase our confidence in regional assessments by amassing a comprehensive set of descriptive exploration models of the type that mining companies had used successfully in the search for new ore deposits. A useful model would list the small- and large-scale attributes of the geologic terranes that had been found to contain ore deposits of a certain type. Armed with a compendium of deposit models, a resource assessor could compare the geology of the area in question with the attributes of the exploration model. If there were enough points in common, the area being assessed would be said to be "favorable ground," to be "prospective," or to have "potential" for the occurrence of deposits of the specific model type.

One benefit of assessing by means of exploration models was the reduction of the volume of information that geologists had to remember. "There are hundreds of types of mineral deposits," Paul Barton used to explain, "and asking a geologist to be conversant with all of them is as unreasonable as expecting a linguist to speak each of the world's languages." Another benefit was the reproducibility of the assessments. We expected that two geologists working on the same area and using the same models would arrive at the same conclusions--most of the time. But perhaps the most important benefit was that the models brought to bear on our problem literally thousands of man years of descriptive and genetic research on ore deposits.

In contrast to the external pressures that encouraged us to develop tonnage-grade models, the use of exploration models arose in response to the scientist's needs to impart rigor to his studies and have confidence in his results.

The potential usefulness of exploration models in regional assessments was probably first broadcast within the USGS at a workshop held in Denver in 1979 (Shawe, 1981). Some of the exothermics that surrounded the land assessment issue were broadcast there, too, but not for the first time. "Characteristics of Mineral Deposit Occurrences" was the earliest compilation of models, an administrative report on a year-long crash program led by Ralph Erickson (Erickson, 1981). About the same time, models began appearing in the Canadian literature (so we knew that we were on the right track), culminating in Roger Eckstrand's handsome volume based on Canadian deposits (Eckstrand, 1984). The most recent USGS compendium is Cox and Singer's matched pairs of exploration and tonnage-grade models assembled as background for an experimental assessment of western Colombia (Hodges and others, 1984). An interesting recent application of models is found in an assessment of the metal endowment of all the wilderness areas in the Pacific Mountain System (Drew and others, 1985). A current activity, in which both Canada and the United States are participating, is a worldwide project on mineral deposit models sponsored by the International Union of Geological Sciences.

CONCLUSIONS

Making mineral resource assessments was not a progressive step that geologists took in order to advance their science, nor was it an activity that they were well prepared to undertake. It was a mission assigned by society. The earliest assessments were presented in carefully worded texts that outsiders viewed as richer in jargon than in substance.

Mineral deposit models became a part of the assessment methodology in response to pressures from both inside and outside the scientific community. Tonnage-grade models fulfilled the policymaker's need for quantitative information on undiscovered deposits. Exploration models fulfilled the scientist's needs for rigor in his work and confidence in his location of areas of mineral potential.

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APPLICATION OF MINERAL DEPOSIT MODELS TO REGIONAL ASSESSMENTS: DISCUSSION

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Among the definitions of "model" offered by a standard dictionary, the phrase "conceptual, idealized representation" applies to deposit models. In effect, geologists are creating a hypothetical representation of a particular deposit type that embodies all known critical and diagnostic criteria for that deposit type. Development of a deposit model generally proceeds in three stages: (1) observations on many imperfect examples; (2) recognition of the common geologic parameters; and (3) synthesis into a composite, idealized model.

Explorationists and resource evaluators alike have found that deposit models are absolutely essential because of the increasing need for predictions required to minimize exploration efforts or land use decisions using a limited local data base. In other words, the list of criteria by which a particular deposit model is defined provides a readily usable checklist of proven favorable variables against which the geology of a potential target area can be compared. This process is particularly useful in those situations where an exhaustive data- gathering process preceding a major decision, whether it be with respect to industry exploration or government land use, is impossible or impractical.

Most, if not all, current deposit models are of the descriptive-genetic type, but economic geologists are now advocating, for certain deposit types, increased research directed toward quantification. For example, with reference to lead-zinc deposits in carbonate rocks (Mississippi Valley type-deposits), Anderson (1983, p. 74-75) argued that "...to have a more useful model or working model, the ideas must be mathematically related to some extent. Our models have not been particularly helpful in prospecting because of this lack of quantification....It's about time we came up with a true model for MVT ores, one which interrelates flow rates, concentrations, and residence times into a single package. Until we do, we are not practicing science but simply speculating on what might have been."

For resource assessment purposes, three major components of a deposit model are required: (1) the descriptive component, which includes diagnostic criteria and permissive criteria, as defined by Pratt (this volume); (2) the genetic component, which constitutes a "test" of the diagnostic criteria and instills confidence in the model; and (3) the grade-tonnage component, which is necessary to convert deposit types to commodities and for quantitative resource estimates.

Ideally, the descriptive component of a deposit model should be established independent of and precede the genetic component. Unfortunately, in many instances, the genetic component has been erected too early in the development process, the result being that (1) it is sometimes based on too few descriptive criteria and the genetic component therefore tends to "drive" the descriptive component and (2) only those criteria that satisfy the current version of the genetic component are recorded. Thus, instead of the descriptive component's being used to construct the genetic component, the opposite tends to happen.

In a thoughtful and well-written discussion of facies models in sedimentary processes, Walker (1984) considered that a facies model must fulfill four important functions. Paraphrased to apply to deposit models rather than facies models, these functions are as follows:

1. The model must act as a **norm** for purposes of comparison.
2. The model must act as a **guide** for future observations.
3. The model must act as a **predictor** in new geologic situations.
4. The model must act as a **basis for metallogenic interpretation** for the deposit type that it represents.

Functions 3 and 4 are particularly appropriate for resource assessment purposes (and, equally, for mineral exploration).

Against all of the foregoing as background, papers presented at this workshop that addressed the application of mineral deposit models to regional assessments will be "revisited" in the discussion that follows.

Paul Barton presented several good points, among them the concept of learning curves as applied to deposit models (his figs. 3, 4). In effect, the position of a particular deposit type on Barton's curve is a statement of the extent to which that deposit type has passed from the descriptive stage to the genetic stage. Although Barton's curves show only "level of genetic understanding" as the ordinate, some deposits shown on his graph as possessing a low level of **genetic** understanding also possess a low level of **descriptive** understanding. Because the deposits are still in the early stages of descriptive-component development, the critical criteria have not yet been recognized, and the distinction between diagnostic and permissive criteria is not possible. Tsumeb and Olympic Dam might be good examples of deposits in this stage of model development. Barton's flow charts (his fig. 9) illustrating the point in the exploration and resource assessment processes at which deposit models are used, focus on the pivotal role that deposit models play in both instances. The main difference between the two flow charts is that, in exploration, the models are used to select target areas; hence, models come into the picture early in the process. In resource assessment, the targets are invariably preselected, and information about the geology in the study area is collected, synthesized, and compared with deposit models later than it is in the exploration process. Barton's flow charts serve to remind us that the basis of resource assessment is a subjective (and quantitative or qualitative) estimate of the degree of fit of regional geology to the model for each deposit type. The better the fit, the higher the potential for that deposit type to occur in the selected area.

Walden Pratt introduced us to the important concept of diagnostic as opposed to permissive criteria. This distinction is, in effect, a weighting of criteria and constitutes the first step down the long road to quantification of variables in deposit models. Once two hierarchies of criteria are established (as in Pratt's example), work can begin on ranking the variables within each group in order of decreasing importance. Ranking the variables and testing the model constitute an iterative process and will require much refinement before an acceptable ranking order is established for any deposit type. Studies such as Pratt's, however, have set us firmly on the road to achieving this necessary goal for resource assessment purposes.

Readers should note that criteria listed by Pratt are not those for Mississippi Valley-type deposits in general but are specifically for deposits of this type in the southeastern Missouri district of the United States. That is to say, they represent an area-specific model, whereas Barton is referring to "use-anywhere" (general) models. These two papers have brought out an important point: the Barton-type model is useful in resource assessments of hinterland areas, whereas the Pratt-type model is most useful in resource assessments of lands peripheral to known mineral districts (in this case, southeastern Missouri). In effect, Barton-type models are transportable, whereas Pratt types are not. Both are deposit models, but their differences reflect the different situations in which they are meant to be applied.

Papers by Stuart Roscoe and Carroll Ann Hodges grappled with the problem of using deposit models for resource assessment purposes in areas where geologic information is minimal. Both authors necessarily employed the "use-anywhere" (Barton) type models in their assessment procedure. The very special problems of carrying out resource assessments in hinterland areas such as those addressed by Roscoe and Hodges is a topic that I feel deserved much more attention at this workshop than it received. A majority of current deposit models embody criteria that, in quality and quantity, are just not available from most geologic maps and reports of hinterland areas or public lands. Thus, in parallel with the continued development of deposit models, resource assessments require constant upgrading of the geologic information base to ensure that the refined deposit models are used to their best advantage; that is, the better they will serve as predictors in the sense required by Walker's analysis of model functions.

Richard Taylor and John Dersch pointed out that, for many users of resource assessments, deposit models must include the grade-tonnage component discussed earlier. This component is necessary to convert the assessment statements from geologic resources (deposit types), which is what most economic geologists work with, to mineral commodities, which is what most users work with or relate to. Specifically, this component is needed to convert the number of deposits of a given type to amounts of contained commodities.

The relation between resources and commodities can be illustrated first by examples from the forestry industry (table 1). Here, the resources are trees of different types; depending on the tree, different commodities are produced. Similarly, in the mineral industry, the resources are deposits of different types, and, again, depending on the type of deposit, different commodities are produced. The important point to keep in mind here is that the mineral resource assessors think, work, and express their estimates in terms of geologic deposit types. The customers who use these estimates, however, commonly require them to be expressed as mineral commodities. The two groups are, in effect, speaking two different languages, much in the manner of two tribes in two valleys on opposite sides of a mountain. What both situations require is the equivalent of a Rosetta stone to translate from the left-hand column in table 1 to the right-hand column (that is, from deposit types to mineral commodities). Components of these Rosetta

TABLE 1.--Resources versus commodities

Resource	Commodity
Trees	
Pine	Lumber
Spruce	Pulp, lumber
Maple	Syrup, lumber
Mineral deposit types	
Porphyry	Copper, molybdenum
Mississippi Valley	Lead, zinc
Layered mafic intrusions	Chrome, nickel
Volcanogenic massive sulfides.	Copper, lead, zinc, silver, gold.
Sedimentary exhalative	Lead, zinc, silver

stones may exist in the form of probability curves such as those shown in figure 1, taken from Singer and Mosier (1983a). These authors have compiled curves relating the probabilities of ore tonnage and commodity grades for several dozen different deposit types. Thus, once a statement of the number of deposits of a specified type has been made for the area being assessed, application of the grade-tonnage probability curves in figure 1 (the Rosetta stone) can convert, in a series of steps, number of deposits to tons of commodity (fig. 2). Probability curves for variables such as tonnage, grade, deposit frequency of occurrence, and so on can be combined into a single probability curve by the Monte Carlo iterative process. A single probability curve derived in this manner would, in effect, constitute the Rosetta stone required to convert a statement of geologic favorability or estimated number of deposits to a statement on commodity abundance. Thus, using Rosetta stones of this nature, the geologist tribe can converse with the economist tribe.

Finally, Jon Scoates and his colleagues leave us with a sobering reminder of the time dependency of deposit model development, using layered intrusions as an example (Scoates and others, fig. 9). The difference between the high potential ratings assigned to nickel-copper and chromium in the one instance and platinum-group elements in the other is that the first three were discovered many years ago as the result of normal prospecting. Platinum-group elements, by contrast, are currently being sought in the complexes because of predictions based on a deposit model developed in the interim, which was the result of observations made on many similar intrusions elsewhere in the world. If, in fact, significant concentrations of platinum-group elements are found in Canada's Bird River Complex, the model will thereby be strengthened by this iterative process. Further refinement of the model may, in the future, prompt yet another examination of layered intrusions for commodities not yet anticipated. Model development is a time-consuming process, as Barton (this volume) alluded, but increased travel by economic geologists, better means of communication and data storage, and the geoscience community's heightened awareness of the usefulness of deposit models will ensure the future quickening of the process.

In conclusion, many good points were raised in the deposit models session, selected ones of which have been touched on in this discussion. I note, however, that the following two very important issues regarding the use of deposit models in resource assessments were not addressed at all:

1. "Supergiant" deposits—what controls their distribution, how they can be accommodated in deposit models, and how they affect resource assessments. The general topic of supergiants has received scant attention in the scientific literature (Laznicka, 1983), yet no one would dispute the economic effects, locally, nationally, or even internationally, of a Kidd Creek, a Sullivan, a Butte, or a Witwatersrand.
2. Estimating the number of deposits in a specified area. Although a number of reasonably good descriptive (Eckstrand, 1984; Cox, 1983) and grade-tonnage (Singer and Mosier, 1983a, b) components of deposit models are available, what is urgently needed is a probability curve to express the number of deposits in the area being assessed. This curve could take the form of frequency of occurrence per unit area or geologic entity. An example of the latter might be Sangster's (1980) analysis of the number of massive sulfide deposits associated with volcanic centers. Obviously, research is needed to provide this missing key element of resource assessments. Without it, the two tribes mentioned previously may forever gesticulate uselessly at each other without hope of proper communication.

ACKNOWLEDGMENTS

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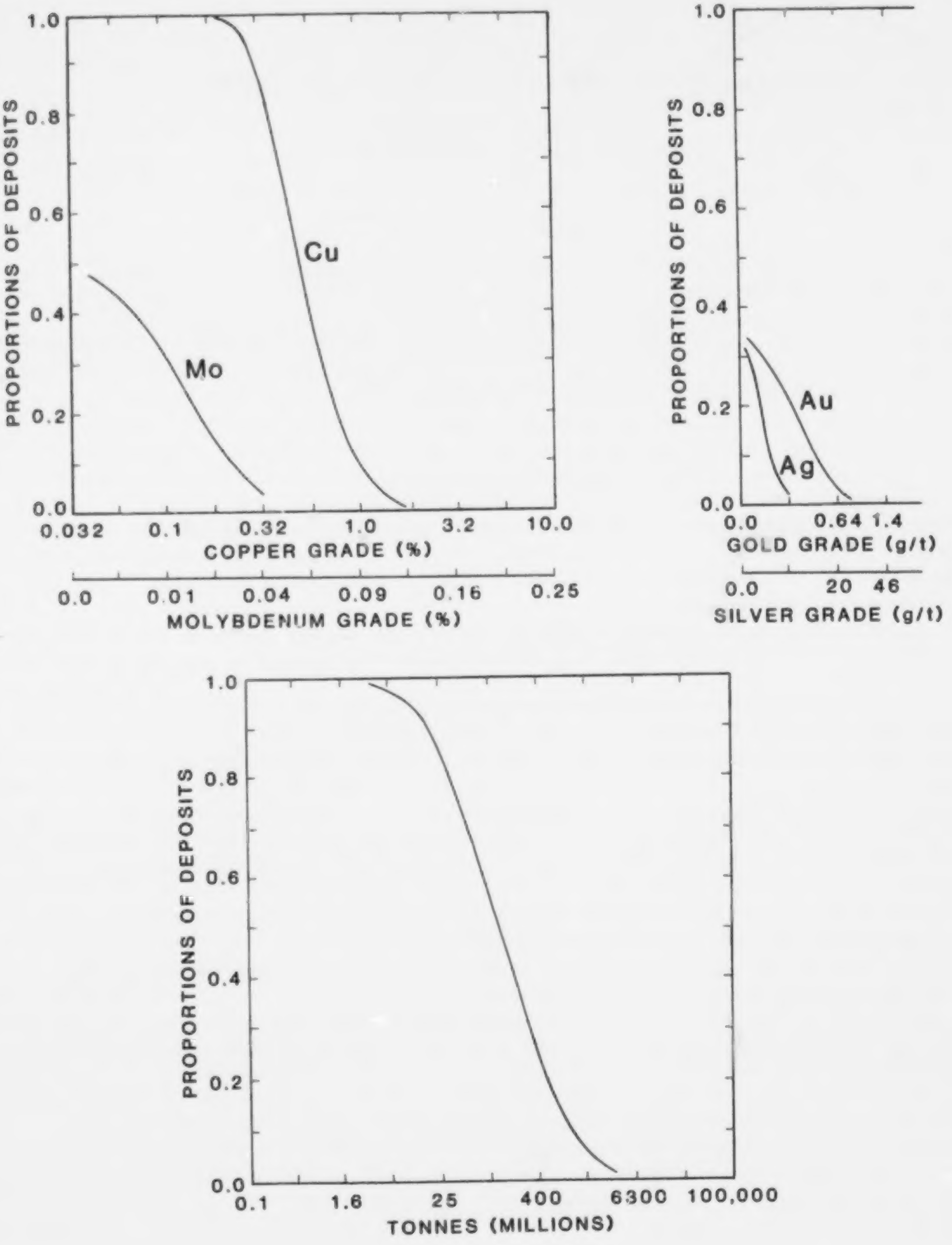

FIGURE 1.—Probability curves for tonnages and commodity grades in porphyry copper deposits (from Singer and Mosier, 1983a).

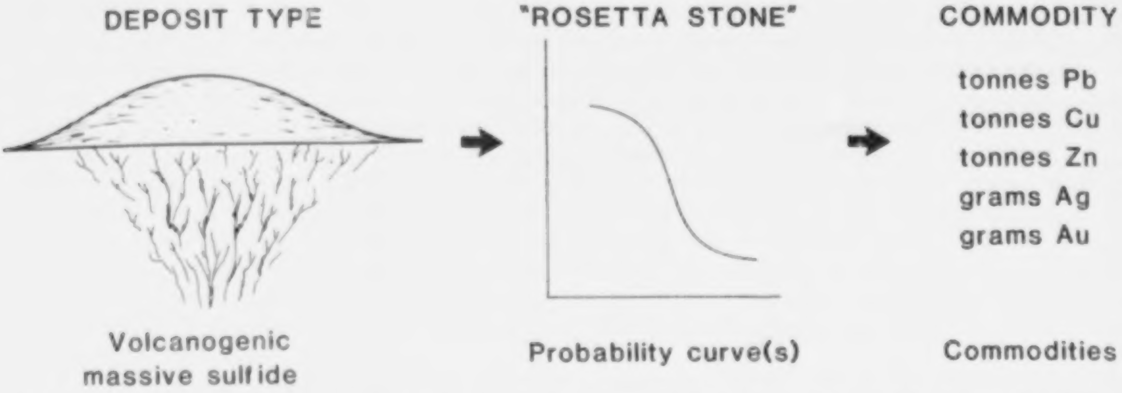

FIGURE 2.--Schematic representation of the concept displayed in table 1 emphasizing the necessity of developing a Rosetta stone to convert resource assessment statements from geologic terms to commodity terms.

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ECONOMIC ASPECTS OF MINERAL RESOURCE ASSESSMENT

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INTRODUCTION

The economic overlay for resource assessment concerns the supply process by which minerals are converted from geologic resources to marketable products. The main elements of this process are portrayed in figure 1. Thus, a geologic stock of resources, concentrated in mineral deposits, flows through a multistage series of mineral sector activities to supply a mineral market.

Various types of resource appraisal can be carried out to examine the availability of actual and potential mineral stocks. Assessments of the cost, risk, and return characteristics of mineral exploration, mine development, mining, mineral processing, and transportation reflect the economics of the sequential conversion process. Finally, commodity economics comprises the documentation and projection of mineral market conditions (supply, demand, and price factors and their interaction) in the context of an overall materials market.

SPECIAL FEATURES OF MINERAL SUPPLY

Special features of mineral supply that are important from an economic point of view can inevitably be traced back to a single distinctive influence: the geologic environment. Four factors embodied in this environment are of particular interest. Mineral deposits, the geologic basis for mineral supply, are initially unknown, fixed in size, variable in quality, and fixed in location.

Since mineral deposits are initially unknown, they must be found and delineated before normal types of industrial development and production decisions can be made. Thus, mineral exploration is an integral part of the mineral sector. (There is a parallel between exploration and research. Both are high-risk information-gathering activities directed toward discovery. In terms of economic evaluation and control approaches, much can be learned from this analogy. However, two important distinctions should also be made. First, technological advances from successful research can usually be transferred much more readily and extensively than the benefits arising from the discovery of an economic mineral deposit. Second, although research results may be important to the success of an industrial enterprise, successful mineral exploration is essential to the survival of mining companies. The two activities are related, research being central to the advancement of exploration technology.)

In the long term, the mineral supply process starts with the search for mineral deposits, where there is not only a typically long period of investment but also a high risk of total loss through failure to discover an economic deposit. One implication of the high risk nature of mineral exploration is the strong random element associated with exploration success. The determination of long-term mineral sector trends is thus a particularly challenging task.

Mineral deposits, once discovered, are fixed in size and therefore subject to exhaustion in the course of production. Fixed deposit dimensions impose technical and economic constraints on the capacity that can be justified for new mine development and

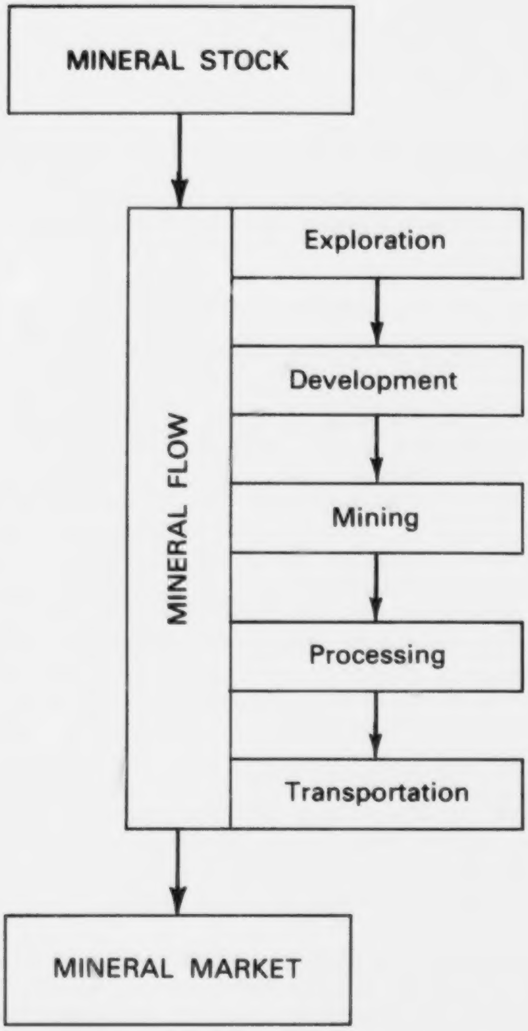

FIGURE 1.--Resource assessment in the context of a supply process.

on the rate of production that can be achieved at existing mining operations. More broadly, for every ton of ore that is mined from a particular deposit, company, region, or country of interest, there is one ton less left to mine. Thus, continuing exploration effort and success are required to maintain existing production levels. The exhaustible nature of mineral resources is also the basis for long-standing concerns about resource scarcity, limits to growth, and the role of mining in economic development.

Mineral deposits are not only geologically fixed in size but are also variable in quality. Variable quality within individual deposits gives rise to planning opportunities in terms of cutoff grade and sequence of mining decisions. Variability in the quality of mineral resources among deposits has a critical influence on a wide spectrum of policy and planning issues relating to, for example, economic rent and mining productivity.

Finally, mineral deposits, not having the benefit of wheels, cannot be moved to the most convenient market locations. Consequently, development, mining, and usually some degree of mineral processing must be carried out where deposits occur. This constraint gives rise to transportation, power, water, and social infrastructure requirements, which, at remote locations, typically represent a major part of capital and operating costs. More broadly, the fact that mineral deposits are fixed in location means that there is often a distinction between resource-rich regions and countries and those areas that are heavy consumers of minerals. This geologic factor explains why mineral commodities are such a prominent feature of domestic and international trade and the source of various global sociopolitical issues.

MINERAL SUPPLY PROCESS

The role of the mineral sector in the economy is to find, delineate, and develop economic mineral deposits and then to mine, process, and market products from them. Thus, economic mineral deposits are the focal point of the mineral supply process. The economic characteristics of the process are shaped by a number of technical features that reflect, in part, the geologic environment associated with mineral resources. Expanding on figure 1, a more detailed portrait of the multistage series of activities by which minerals are converted from unknown resources to marketable commodities is shown in figure 2.

The physical occurrence of mineral deposits in nature and the demand for mineral commodities in the economy provide the basic stimulus for mineral supply. Exploration geologists' and market researchers' favorable perceptions regarding these geologic and market parameters combine to guide the selection of environments for exploration.

The mineral exploration phase is a sequential information-gathering process. In the primary exploration stage, potentially favorable areas of land are selected within an environment of interest, and these areas are then subjected to a series of geologic, geophysical, and geochemical tests. The successful result of primary exploration is the discovery of mineral occurrences. At this stage, the ultimate size and value of each mineral occurrence are unknown.

When sufficient delineation has been completed, a decision is made as to whether a mineral deposit should be developed to production. If the characteristics of the delineated deposit justify mine development, what is perceived to be an economic mineral deposit is the end result of mineral exploration.

The development phase establishes productive mining capacity. Mineral processing is also usually required to upgrade the mine product to a concentrate before transportation and sale. Thus, the construction of processing facilities is carried out in phase with mine development. The installation of a concentrator at the mine site may be required, or a common processing facility may be used to treat ores from a number of mines in a region.

When a mine has been developed and related processing facilities constructed, the production phase commences. The mining stage may include stripping of waste for open pits, preparing stopes for underground mining, developing ore reserves, drilling, blasting, transporting materials to the processing facilities, filling mined-out stopes, and associated technical and planning services. To illustrate, the processing stage for base-metal operations usually includes crushing, grinding flotation, drying, disposing of tailings, and loading concentrate products for shipment. In this way, the ore produced from a mine, which might contain 2 percent copper and 5 percent zinc, can be upgraded to produce a 25-percent copper concentrate and a 55-percent zinc concentrate, with 10 percent of the copper content and 20 percent of the zinc content being lost in the tailings. The mineral commodities produced at the mine site can then be transported to smelting and refining facilities for further processing before being dispatched for sale in the marketplace.

The economic features of the mineral supply process are shaped by three dynamic forces.

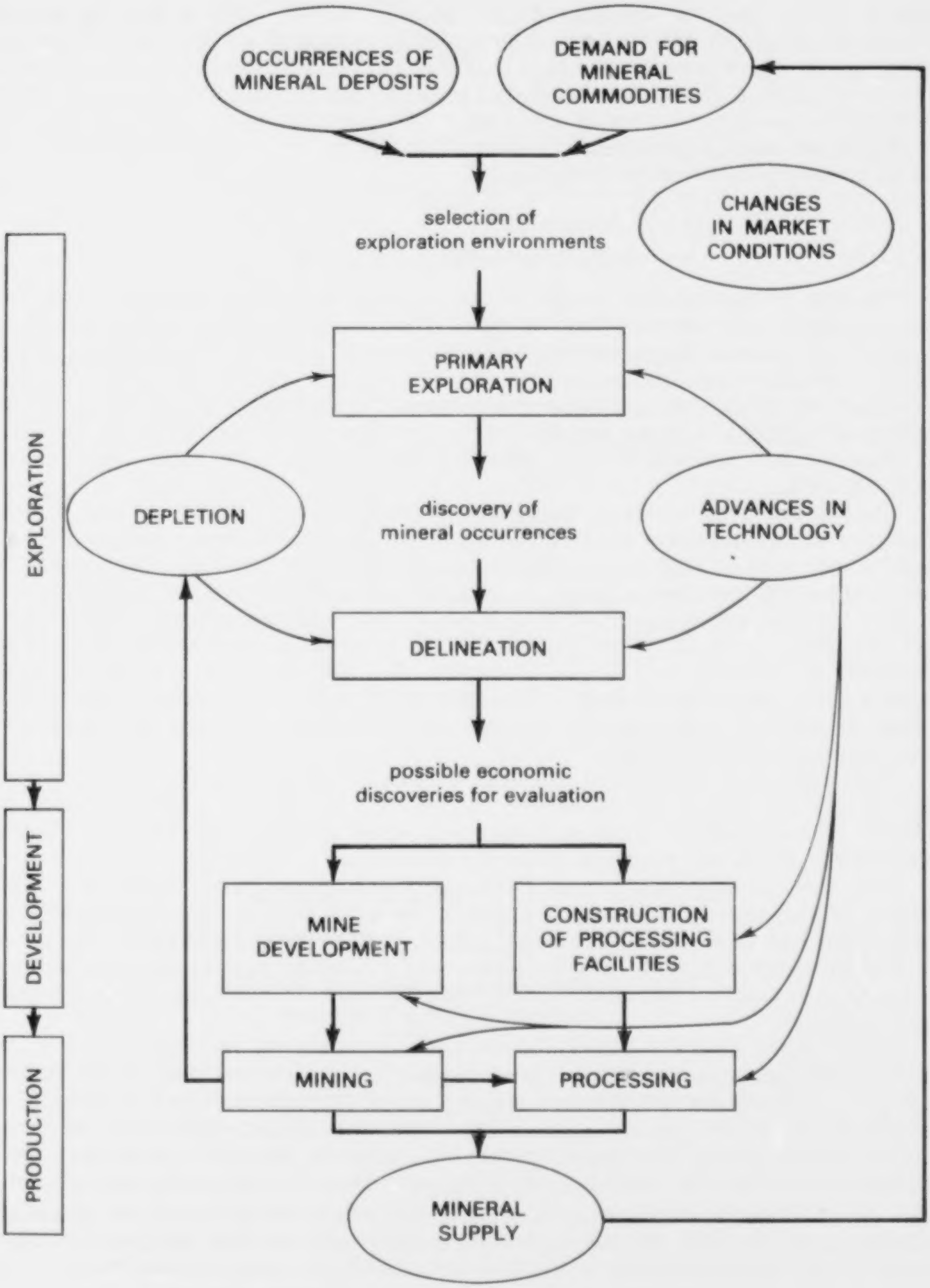
OCCURRENCES OF MINERAL DEPOSITS
DEMAND FOR MINERAL COMMODITIES
selection of exploration environments
CHANGES IN MARKET CONDITIONS
PRIMARY EXPLORATION
DEPLETION
discovery of mineral occurrences
ADVANCES IN TECHNOLOGY
DELINEATION
possible economic discoveries for evaluation
MINE DEVELOPMENT
CONSTRUCTION OF PROCESSING FACILITIES
MINING
PROCESSING
MINERAL SUPPLY
EXPLORATION
DEVELOPMENT
PRODUCTION

FIGURE 2.--The mineral supply process.

1. The market demand for mineral commodities changes with time owing to a number of factors, including the varying requirements of existing end uses, changes in the properties and relative costs of substitute materials, the development of new product markets, and modifications in transportation, smelting, and refining conditions.
2. Depletion, the physical exhaustion of mineral deposits, is inherent in their exploitation. Thus, continual exploration is required to sustain existing levels of mineral production. Furthermore, exploration, guided by geologic concepts and skills, is a systematic process in the long term, tending to detect first those deposits that are largest, of the highest grade, closest to the surface, or closest to market. Consequently, the deposits that are the best and easiest to find will, on average, be discovered, developed, and exhausted first. Deposts that are of lower quality, smaller, or harder to find remain for the future. Thus, depletion causes the cost of mineral supply to rise over time.
3. Fortunately, a third offsetting dynamic force is also at work: advances in technology. Such advances may include more efficient and extensive exploration techniques and improved mining and mineral processing methods. Advances in technology act to reduce the cost of mineral supply.

The results of these market, depletion, and technological forces determine whether the economics of mineral supply is in fact deteriorating or improving with time.

ECONOMIC PARAMETERS AND CRITERIA

The economics of mineral supply comprises the costs, risks, and returns of the three-phase process. Since the focus of the process is economic mineral deposits, the economics of mineral supply can be conveniently measured by the relation between the exploration expenditures required to find and delineate an economic deposit and the net return associated with the subsequent development and production of that deposit. These parameters can be thought of as C, p, and R, where C is the typical or average exploration cost associated with the discovery of a mineral occurrence, p is the probability of an economic mineral deposit, given the discovery of a mineral occurrence, and R is the average return associated with an economic mineral deposit.

Thus, C represents the exploration expenditure required for a technical success. R is the motivator of the supply process, the prize resulting from an economic discovery. The connecting link between the cost and return parameters is the discovery risk, the chance or probability of success each time (p). In general, mineral supply is characterized by a high discovery risk and a large possible return from an economic discovery relative to the cost of discovering a mineral occurrence.

Sometimes, it is convenient to combine the cost and risk parameters in a single measure for assessment purposes. Thus:

$$E = C/p$$

where E is the average exploration cost required to find and delineate an economic mineral deposit.

Assessments of the costs, risks and returns of mineral supply are applied to measure the economic attractiveness of the process. Economic criteria may be conveniently subdivided into long- and short-term considerations. Long-term attractiveness is evaluated by using measures of expected value. The short-term problems associated with realizing expectations are assessed by risk criteria.

Expected value criteria measure the average value that mineral supply yields in the long term, when the successes and failures associated with a very large (theoretically infinite) number of discoveries are considered. For example, the expected value (EV) of the mineral supply process per economic discovery considers that an exploration expenditure E is required, on average, for the discovery of an economic deposit, the average return being R. Thus,

$$EV=R-E=R-(C/p)$$

On the basis of assessment of the costs, risks, and returns of the supply process, expected value criteria are derived from the time distribution of average cash-flows for the discovery of an economic mineral deposit. This distribution is initially evaluated on a potential value or before-tax basis as portrayed in figure 3. The potential value of mineral supply, including all direct costs and revenues through the three-phase mining cycle, measures the productive capability of mineral resources to society and indicates what is available for sharing between industry and government before taxation considerations. Then, to provide measures of investment incentive from a mining company's viewpoint, the potential value assessment can be converted to an after-tax basis, as figure 4 depicts. The mining company decides, on an after-tax basis, whether it is worth while to invest in the mineral supply process.

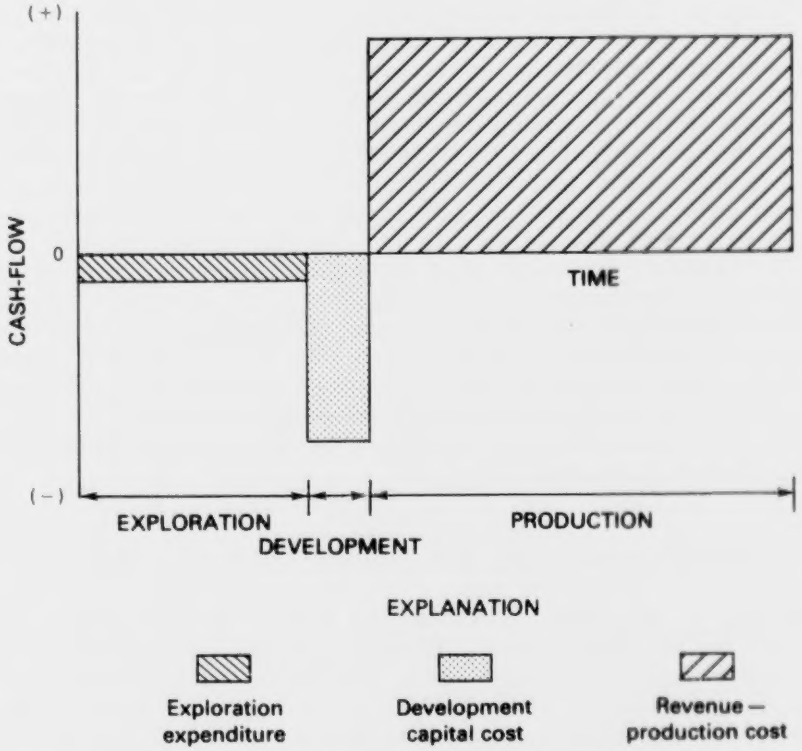

FIGURE 3.—Potential value of an economic mineral deposit based on the time distribution of average cash-flows.

Three main types of risk are associated with the realization of expected values:

1. The sensitivity of the economics of mineral supply to uncertainties in metal prices.
2. The uncertainty of the return from an economic discovery arising from geologic variability among deposits.
3. The risk associated with the discovery of economic mineral deposits.

These risks, individually and collectively, present challenges to the long-term profit, survival, and growth of organizations participating in the mineral supply process.

The first type of risk is associated with the materials market for mineral commodities. There is typically a high level of uncertainty associated with the forecasting of short-term fluctuations and long-term trends in mineral market prices, including exchange rate risks. The economics of mineral supply is highly sensitive to prices. Flexibility in the planning process is required to contend with the unexpected changes in market conditions that inevitably occur. Corporate strategies can be adopted to address this risk. For example, exploration may be focused on polymetallic deposits or spread among several deposit types.

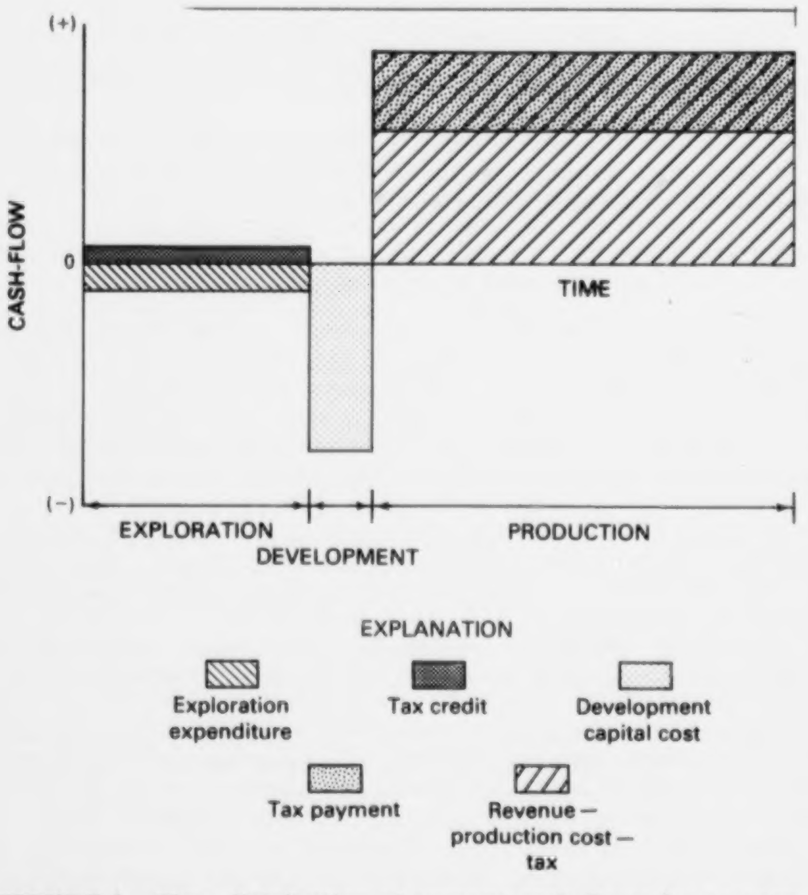
(+)
CASH-FLOW
0
(−)
TIME
EXPLORATION
DEVELOPMENT
PRODUCTION
EXPLANATION
Exploration expenditure
Tax credit
Development capital cost
Tax payment
Revenue — production cost — tax

FIGURE 4.—Time distribution of average cash-flows for an economic deposit after tax.

The second main risk is the variability of the return, given the discovery of an economic mineral deposit. The downside risk and upside potential associated with the variability of geologic parameters among deposits have important implications for corporate planning. The possibility that any exploration program can lead to a multibillion dollar discovery, although extremely unlikely, is no doubt a great motivator of investment in mineral supply. Such a giant target likely carries weight in investment decisions beyond its actual numerical contribution to the expected value function.

The third type of risk is the discovery risk faced in mineral exploration—that is, the low probability of an economic mineral deposit, given the discovery of a mineral occurrence. Typically, there is a 0.01 to 0.02 chance of an economic deposit, given such a technical success. The practical implication of discovery risk is the large difference between the average exploration expenditure required to find and delineate an economic deposit and the exploration funds required to ensure success. The level of exploration funding (A_r) required over a relevant planning horizon to have a reasonable degree of confidence or insurance of discovering at least one economic deposit ($P\geq 1$) can be evaluated as follows:

$$A_r = -E\,[\ln(1-P_{\geq 1})]$$

For example, if $P\geq 1=0.95$, $A_r=2.99E$. In other words, the investment required to be 95 percent sure of exploration success is approximately three times greater than the average expenditure per economic discovery. Owing to the high discovery risk that characterizes exploration, the application of limited investment funds does not ensure the realization of expected values, and exploration resources can be expended without success.

Given these parameters and criteria, economic aspects of resource assessment can be considered from the vantage points of government and corporate organizations responsible for the mineral supply process.

ILLUSTRATIVE EVALUATION PROCEDURE

The economic characteristics of the mineral supply process can be assessed in various ways, depending on the availability of data and the intended application. Most approaches begin by appraising the physical occurrence of mineral resources and then simulate the economics of converting these resources, through the sequential process of exploration, development, and production, into marketable commodities. The illustrative evaluation procedure outlined here bypasses the physical occurrence step and endeavors to make a direct empirical appraisal of the mineral supply process itself.

The main goal of the evaluation exercise is to provide broad guidelines for mining company planning and government mineral policy formulation. To provide meaningful assessments, the long-term nature of the mineral supply process requires the use of an extensive historical timeframe of data and a perspective of the future that goes well beyond the prevailing economic conditions. Relevant historical experience is documented and then evaluated in the context of present-day economic and technological conditions.

This methodology enables us to assess the potential economic value of mineral supply, defined as the difference between the revenues realized from mineral production and all the costs required to realize that revenue, including an allowance for the cost of capital. Since the cost of capital is deducted, this potential value represents the increase in real wealth that results from investing in mining rather than in some other economic activity. Thus, potential value reflects both the quality of mineral resources and the economic viability of mineral supply. It also measures the productive capability of the mineral sector and represents what is available for sharing between industry and government before policy considerations.

This potential value is determined by the costs and revenues of the exploration, development, and production phases of the mineral supply process. Since the focus is economic mineral deposits, it is appropriate to assess potential value on the basis of the number of economic deposits and the time distribution of average cash-flows associated with an economic deposit (fig. 3). Discounted cash-flow methods are applied to this average cash-flow distribution to evaluate various expected value criteria. It is also necessary to consider the risks associated with realizing these expectations and their implications. Thus, the effects of discovery risk, price uncertainties, and the variability of returns among economic deposits are examined.

In the evaluation procedure outlined here, the expected value and risk characteristics of mineral supply are evaluated on the basis of historical footprints. In attempting to detect and project time trends, two assumptions are nevertheless necessary in planning for the future:

1. Deposits yet to be found will resemble, in economic terms, those that have been discovered to date.
2. The cost of making a future discovery will be similar to past costs.

Thus, assessment of the cash-flow characteristics associated with mineral supply is based on the documentation of actual experience over a relevant historical time period. This information is then placed in the context of current outlook conditions.

In essence, the methodology outlined in figure 5 follows these steps:

1. Total exploration expenditures are estimated for the historical time period of interest.
2. Significant deposits discovered as the result of these expenditures are classified by discovery date and listed for evaluation.
3. The development and production phase characteristics for each possible economic discovery are evaluated on the basis of present-day conditions.
4. Those discoveries that, on evaluation, satisfy minimum acceptable size and profitability conditions are considered to be economic deposits.
5. The development and production phase characteristics of all economic deposits are averaged.
6. Total exploration expenditures, which cannot in general be directly associated with the economic discoveries, are prorated across all economic deposits evaluated.
7. The exploration phase estimate is integrated with the average development and production phase characteristics to portray the time distribution of average costs and revenues for an economic deposit from the start of exploration to the end of production.
8. Several expected value and risk measures, reflecting the potential value of mineral supply, are derived from these results. Time trends in these indicators reflect the changing geologic character of mineral resources.

More specifically, the development and production phase characteristics for each possible economic discovery (step 2) is evaluated (step 3) as shown in figure 5 by combining general estimates of metal prices and smelter payment terms with estimates of recoverable ore reserves for individual deposits; mill recovery factors; mine and mill capacities; capital costs, including the working capital requirement; preproduction development period; and operating costs. These estimates, based on the actual historical record, attempt to portray how each deposit would look today if it were awaiting development. A number of measures of economic worth are derived from the resulting cash-flow distributions, including the total sales revenue generated and the rate of return. Those discoveries that satisfy minimum acceptable total revenue (size) and rate of return (profitability) conditions are deemed to be economic (step 4). The cash-flow estimates for all economic deposits are then averaged (step 5), resulting in a time

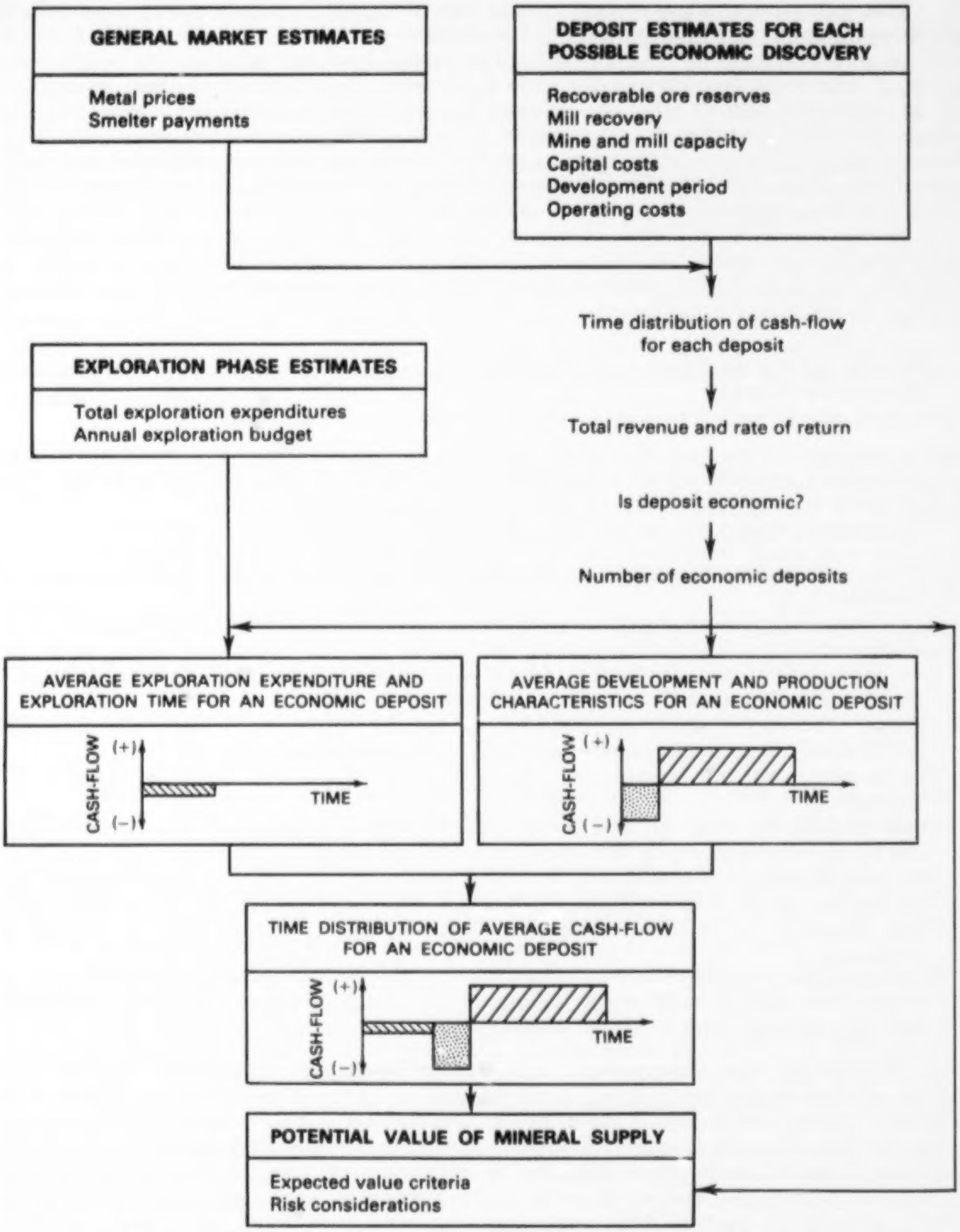
GENERAL MARKET ESTIMATES
Metal prices
Smelter payments
DEPOSIT ESTIMATES FOR EACH POSSIBLE ECONOMIC DISCOVERY
Recoverable ore reserves
Mill recovery
Mine and mill capacity
Capital costs
Development period
Operating costs
Time distribution of cash-flow for each deposit
EXPLORATION PHASE ESTIMATES
Total exploration expenditures
Annual exploration budget
Total revenue and rate of return
Is deposit economic?
Number of economic deposits
AVERAGE EXPLORATION EXPENDITURE AND EXPLORATION TIME FOR AN ECONOMIC DEPOSIT
CASH-FLOW
(+)
(−)
TIME
AVERAGE DEVELOPMENT AND PRODUCTION CHARACTERISTICS FOR AN ECONOMIC DEPOSIT
CASH-FLOW
(+)
(−)
TIME
TIME DISTRIBUTION OF AVERAGE CASH-FLOW FOR AN ECONOMIC DEPOSIT
CASH-FLOW
(+)
(−)
TIME
POTENTIAL VALUE OF MINERAL SUPPLY
Expected value criteria
Risk considerations

FIGURE 5.--Evaluation procedure for assessing the economics of mineral supply.

distribution of average cash-flows for the development and production phases of the mineral supply process.

With respect to the exploration phase appraisal (step 6), the total exploration expenditure estimate (step 1) is divided by the number of economic deposits assessed (step 4) to determine the average exploration expenditure required to find and delineate an economic deposit. This average exploration expenditure is then divided by what is assumed to be the most efficient annual exploration budget rate to evaluate the average exploration time that would be needed to make an economic discovery. These exploration phase estimates are then integrated with the development and production phase appraisals.

As figure 5 portrays, the result of this evaluation process is an assessment of the time distribution of average cash-flows for an economic deposit over all three supply phases (step 7). Indicators of the potential value of the process can then be derived from these estimates (step 8).

This type of potential value assessment provides a useful standard for evaluating the direct effects of government policies, in areas such as taxation or environmental control, on the economics of mineral supply. Imposition of appropriate policy options on the potential expected value and risk indicators enables appraisals to be made of the efficiency of the policy, government revenue effects, and corporate investment incentive.

CHAIRMAN'S SUMMARY

By William A. Vogely
Pennsylvania State University

INTRODUCTION

This summary presents, as nearly as I can reconstruct them, the oral remarks that I made at the workshop. However, in the several-week period that I was given to write up these remarks, an important point occurred to me, and I have included that point in this paper. Several major points jumped out at me from this workshop. The first is that I feel that geologists are not communicating clearly with the policy-level people whom they serve as expert advisors. The second concerns the state of the art for resource appraisal. The third involves the neglect of demand as a necessary factor in creating a valuable mineral deposit (that is, an orebody).

Communication Issues

The U.S. Geological Survey (USGS) provides maps showing areas within a region where it has found high, medium, and low mineral potential. At issue is what these labels mean to the USGS and to decisionmakers. At the workshop, it was clear that the USGS means to imply nothing about the economic value of these areas; their ranking is based only on mineral concentrations. Decisionmakers, on the other hand, apparently assume that high-rated areas have economic potential--unquantified but positive. One session argued that economic potential should be at least qualitatively included in the rankings. I go further. I agree that the USGS cannot be expected to predict whether an area of high potential, if explored, would prove to contain an orebody that would support an active mine under the prevailing economic conditions and how valuable that mine might be. I do, however, think that the USGS could use the same logic of estimation that it used for mineral potential to provide the expected unit regional value (URV) of the three area types. The URV estimate is based on developing a geologic analog for an area of interest based on an area that has already been explored and developed. Mineral potential estimates, prepared through complex manipulations, are also often based on developing a geologic analog with an area that has been explored. Why is it acceptable to transmit one result but not the other?

Assessment Technique Issue

What is being estimated? The most elaborate system, which was presented by Larry Drew, gives the number of deposits and tonnage and grade distributions for each mineral. Isn't a deposit, by definition, a concentration of minerals that somewhere, at some time, had been ore (that is, it was once economically producible)? I understand resource appraisal to be an estimate of mineral concentrations (deposits that are at least potentially economic). Given this understanding, I am baffled by the resistance to interpreting areas of high potential as having positive economic value.

Role of Demand

What was missing altogether from the workshop was a discussion of mineral demand. A mineral deposit, regardless of tonnage and grade or location, has no value to society unless its contents are demanded by that society. The economic axis of the McKelvey box needs demand to be relevant. A known deposit has no value unless someone thinks that the contents of that deposit will be in demand and is thus willing to invest to gain ownership or control of the deposit.

THE NEW POINT

An obvious point follows from the above, but I did not see it during my oral presentation. Resource assessment is not a task for geologists alone. To assign the task to them is a clear mistake by the decisionmaker. To demonstrate, I refer to my recent article in Materials and Society, which was reproduced and used at the workshop (Vogely, 1984).

Supply Theory and Resource Assessment

In my article, I argued that mineral supply is a flow, not an exhaustion of a fixed stock. I stated that estimates of potential supply in the form of sock figures for the upper right-hand section of the McKelvey box are not appropriate for addressing the "we are running out of mineral X" statement. I did agree that resource appraisal was still useful, "...so long as it leads to a better under standing of resource endowment and can improve the efficiency of exploration and research on new technologies" (Vogely, 1984, p. 600), I also stated that, "Resource assessments of the stock type are useful policy and investment guides for small well-defined geologic and geographic areas..." (Vogely, 1984, p. 600). It is this last statement that I now feel must be withdrawn or elaborated.

Information Required for Efficient Land Use

Regardless of legislative language, I take as given that decisions about the use of public lands should maximize the welfare of society. To that end, the decisionmaker must have data or estimates that reflect the contribution of each possible use of a given area of land to the general welfare. For the USGS and the Geological Survey of Canada, at issue at the workshop was the mineral potential of land that is being classified in such a way that exploration for minerals is being prevented. All of the methods presented at the workshop provide estimates of resource occurrence at a level of detail dependent on the estimation methodology. Even if these estimates were to be made absolutely certain (that is, zero range of error), they would not provide what the decisionmaker needs to ensure that the land is used for the highest social welfare. Social welfare is usually measured by the economic contribution of the land. Although wilderness values cannot easily be converted into dollars, estimates of the economic values given up to preserve a wilderness can be used by decisionmakers as a tool for evaluating the values of unmeasured wildernesses. The higher the foregone values, the greater the chance that the land should not be declared wilderness.

Estimation of Mineral Resource Values

The geologist provides a necessary, but not completely sufficient, input to determining potential mineral resource value. An area must contain minerals, those minerals must be demanded by the economy from that particular area, and they must be producible and transportable to the point of demand at a cost equal to or lower than that of any other supply at the demand point. Societal welfare is increased only if the resource cost of production and transportation is less than the cost of other supplies; that is, there must be some economic rent attributable to the deposit or its location. Thus, estimation of resource value requires:

1. Estimation of mineral occurrence (a geologist's job).
2. Forecasts, for each mineral commodity that occurs, of the demand and supply situation and of future price (an economist's job).
3. Estimates of production cost, including exploration, development, and transportation for each mineral commodity (the job of mining engineers and other engineering professionals).
4. Estimation of the time stream involved and calculation of the net present value to society of using the land for minerala (the job of an economist or a soothsayer, as you wish).

In short, geologists can provide, at best, only one necessary bit of information. A resource appraisal to provide what a decisionmaker needs cannot be done by geologists alone. Even using the URV technique that I called for does not do the job. But it does provide an estimate of the highest gross mineral values that could occur through time, if the demand for the minerals in an area were as great as that in the analog area. If the decisionmaker is happy to compare this maximum mineral value with the unmeasured value of a wilderness area, he at least has more than the estimate of mineral potential stated in physical weight. Sometimes the decision is easy. A very favorable geology for petroleum can quickly be translated into an economic value. Rules of thumb can perhaps be developed to translate the URV estimate to a closer estimate of pet present value for the minerals in a subject area.

Decisionmakers are asking geologists to do something that is beyond their professional responsibilities. Both parties are thereby frustrated, as are others like myself, who study the issue from outside.

CONCLUSIONS

It perhaps is too much to hope that society will make rational welfare decisions about the use of public lands. The way in which the U.S. Government is trying to make these decisions is placing great strain on the USGS, a very important and valuable organization. That level of strain was evident in the response to my oral presentation, even though the presentation did not carry my thinking to its ultimate implications, as I have done here. I hope that my discussion has shed some light on the underlying situation and helps us to understand why resource appraisal and public land use seem to be such intractable subjects. As an economist who has been both an advisor to public land decisionmakers and an analyst of public land use, I question the notion that society is best served by requiring that use of these lands be determined at the Federal management level. Perhaps there is strength to the argument that, except for lands where public values are clearly dominant, society would be better served by a program of disposal rather than management of the land areas of the United States now held by the Federal government.

REFERENCE CITED

Vogeley, W. A., 1984, Resource assessment and the theory of mineral supply: Materials and Society, v. 8, no. 4, p. 597-600.

EPILOG

In 1841, the Canadian Legislature assigned William Edmund Logan the formidable task of assessing the mineral potential of upper Canada as part of a general geological survey. Financed by a grant of 1,400 pounds, Logan's ambitious program of fieldwork and office study laid the foundations of the Geological Survey of Canada.

One hundred and thirty years later, the concept of resource assessment brought together representatives of the U.S. Geological Survey and the Geological Survey of Canada and their colleagues in the public and private sectors to discuss mineral resources on public lands. Although resource assessment was the dominant theme of the meeting, held in Leesburg, Va., in September 1985, it soon became apparent that delegates were also holding informal discussions on a wide variety of subjects, including geology, geochemistry, geophysics, and mineral policy. Conversation and correspondence with delegates during and after the workshop confirmed a growing interest in the type of bilateral exchange that took place in Leesburg.

In response to that interest, the organizing committee proposes that a biennial meeting be convened to consider topics of common interest to the U.S. Geological Survey and the Geological Survey of Canada. Such a workshop, held under the auspices of these two organizations, will also include representatives of government, industry, and the academic community. Topics for discussion need not be restricted to resource assessment but should reflect contemporary subjects that lend themselves to a cooperative study approach. The proceedings and conclusions of the workshop should be published as rapidly as possible, either as a U.S. Geological Survey Circular or a Geological Survey of Canada Miscellaneous Report. The location of the workshop should alternate between Canada and the United States; the early autumn date should be maintained, however, so as not to conflict with fieldwork or with other meetings such as the Geological Society of America annual meeting.

In recognition of the importance of such a workshop and to honor the early work of Sir William Logan in resource assessment, the organizing committee proposes that this biennial meeting hereafter be known as the Logan Workshop.

APPENDIX 1

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APPENDIX 2.—CHARGES TO DISCUSSION GROUPS

DISCUSSION GROUP 1

THE ROLE OF MINERAL RESOURCE ASSESSMENTS IN PUBLIC POLICY FORMULATION

PARTICIPANTS	GROUP A:	D. Christopher Findlay (leader), Jack Schanz (reporter), Gus H. Goudarzi, Robert L. Lawton, Stephen D. Ludington, Edwin H. McKee, Owen E. Owens, Walden P. Pratt, John H. Schuenemeyer
	GROUP B:	David A. Brew (leader), Jan Boon, William Condit, James F. Davis, C. Thomas King, Robert Learned, Susan Marcus, Peter Money, Robert Schrott

Techniques in resource assessment have advanced significantly over the past 10 years or so. However, mechanisms for incorporating the results of assessments into the policy formulation process and for ensuring that they play a useful role in the design of balanced policies may still be difficult, erratic, and bureaucratic.

Resource assessments can aid governments in discharging stewardship responsibilities in the wise use of resources on public lands and in formulating policies for resource management, particularly in the case of strategic resources. They also provide a means for identifying and documenting public lands favorable for the exploration, discovery, and development of mineral and energy resources by industry to ensure needed future supplies. To make effective use of this capacity requires that good mechanisms be in place to transmit the results of resource assessments into the policymmaking process. Since the processes of resource assessment and policymaking are commonly detached (professionally and administratively), such mechanisms may be far from perfect. Experience in Canada at least suggests that a process of education is required on both sides. Scientists need to transmit complex results in nontechnical terminologies to be understood by policymakers, politicians, and the public. Administrators and policymakers need to appreciate the difficulties and uncertainties in "counting" undiscovered mineral and fuel deposits and of deriving economic valuations from infirm foundations.

SELECTED ISSUES

1. How have the roles of resource assessment evolved? What are the comparisons and contrasts, for example, between petroleum resource assessments and mineral assessments? How much use of mineral assessments has actually been made? In policy formulation (for example, land use policy)? In exploration? In designing national policies for strategic materials?
2. What are the present mechanisms (U.S. and Canadian) for using resource assessments in public policy? How have they evolved? How successful have they been?
3. Who/what are the players in the process? What are the various responsibilities (State/Provincial; Federal; interdepartmental, and so on)? How are they coordinated? Are they?

4. What do policymakers want/need? How much is enough? What are the kinds of things that resource assessment can yield for policy formulation? If numbers (quantitative assessments) are required, how are they used (do caveats become detached from numbers)? Are numbers really necessary on many cases?
5. If the formulation of public policy is a public process, how do other (nongovernmental) interests (for example, industry) participate? How can government resource assessments benefit from contributions by groups with specialized knowledge (corporations, universities, independent research institutions, and so on)?
6. What are the probable trends for the future? Will demands (for resource assessments) increase? Decline? Disappear?

DISCUSSION GROUP 2

METALLOGENY AS A FIRST STEP TO MINERAL ASSESSMENTS ON PUBLIC LANDS

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Application of metallogenic principles is, ideally, the most effective way to apply combined regional geology and mineral deposit expertise to the problem of resource assessment. Uncertainty exists, however, in several aspects of this procedure.

If metallogeny is regarded as the relation between mineral deposits and regional geology, perhaps many geologists would regard as self-evident the concept that metallogeny should be the first step in mineral resource assessment. In the strictest sense, however, metallogeny cannot be carried out in the absence of known mineral deposits, a not uncommon situation in resource assessment programs, particularly those on public lands. Thus, the concept becomes not one of performing metallogenic studies in the area under investigation but one of extrapolating into that area metallogenic experience gained in other areas of comparable geology. This leads to the realization that extensive metallogenic experience may actually be the first step required in mineral resource assessments. An additional factor that needs to be considered in this context is that, in order to extrapolate metallogeny for resource assessment purposes (a process sometimes referred to as "predictive metallogeny"), a sifficient geologic data base must exist for the study area. A not uncommon characteristic of public lands, either through legislation (United States) or remoteness (northern Canada), is their relatively poor geologic data base. In many areas, reconnaissance-scale geologic mapping is the norm, and experience has shown that this level of geologic data base is insufficient for metallogenic purposes. In the absence of a proper data base, two possible courses of action can be envisaged before metallogenic studies can be pursued: (1) the area can be (re)mapped with metallogenic principles specifically in mind ("metallogenic mapping") or (2) the area could be covered by remote sensing methods (geochemistry, geophysics) and metallogeny used to augment these results in conjunction with the existing regional geologic data base. Thus, depending on the situations pertaining to specific areas, application of metallogenic principles may, in fact, be the third or even the fourth step to mineral resource assessment on public lands.

Application of metallogeny to resource assessment is most commonly based on the principle of conceptual models of selected deposit types. By this method, the common and obvious geologic parameters of many deposits of the same type are combined to erect a hypothetical or ideal descriptive and genetic model for each deposit type. Both regional and local geologic features are an integral part of the conceptual model, but it is the former that are used most extensively in mineral resource assessments.

The advantage of the metallogenic approach to resource assessment is that it characteristically makes the best use of available expertise, time, and data. Balanced against this are features such as the subjectivity of the method and the fact that it is very model dependent.

SELECTED ISSUES

1. What resources (human, material, and information) are required before metallogenic principles can be applied to mineral assessments on public lands?
2. At what point(s) in the assessment process is metallogeny most effective? Before new data are acquired? After? Continuously?
3. In the areas of insufficient geologic information, what role can remote sensing play in the assessment procedures and (how) can these data be integrated with the metallogenic approach?
4. What are the advantages and disadvantages of the conceptual model approach to predictive metallogeny? Is there a better alternative?
5. Can the metallogenic approach lead to quantitative assessments? Are quantitative assessments desirable or even necessary?
6. If application of metallogenic principles to resource assessment is indeed model dependent, which deposit models do we currently have the most confidence in? Which are the critical ones requiring substantially more and (or) immediate research?
7. Metallogeny in resource assessment is commonly expressed in terms of deposit types (for example, volcanogenic massive sulfides). Most users of assessment reports, however, are nongeologists who prefer (or require) that the assessments be stated in terms of mineral commodities (Cu, Ni, Pt, Au, and so on). What is the best way to make the transition from the assessment method to the reporting method?

DISCUSSION GROUP 3

DEPOSIT MODELS: A QUANTITATIVE BASIS FOR RESOURCE ASSESSMENTS

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Successful application of metallogeny to predict the mineral potential of unexplored terranes requires that the characteristics of mineral deposits (for example, the models) be well established, in the regional context as well as for the deposits and their immediate surroundings. Our collective knowledge of mineral deposits from either the descriptive or the genetic viewpoints is limited; moreover, misinformation is firmly but cryptically embedded in the existing body of "knowledge."

Conceptual models that describe the essential attributes of groups of similar deposits have had a long and useful role in resource exploration and development. However, only recently has emphasis on producing a systematic and comprehensive array of models become popular. Even more recent are the attempts to use this body of information to make systematic assessments of regional resource endowments. Models provide a relatively quick synthesis of a great deal of information that may be useful to the explorationist, the resource assessor, the land use policymaker, the student, and the research manager. The models enable the geologist to compare his observations with the collective knowledge and experience of a wide group of experts.

Every mineral deposit, like every fingerprint, is different from every other in some finite way; thus, models must pass beyond the specific descriptions to broader generalizations before they can become useful. We may not know why a certain feature is in many deposits, but we can use that shared feature to categorize deposits. Eventually, the reasons for mineralization being associated with specific attributes are recognized, and that aspect of the model evolves from descriptive to genetic. Grade and tonnage models are particularly desirable because they provide a quantitative guide to the most probable economic importance of yet-to-be located discoveries.

There are perhaps a hundred different important types of nonfuel mineral deposits for which models have been proposed. By contrast, the number of comparable models for fossil fuels probably would be less than a dozen, perhaps only four or five This multiplicity of possible types mean that the data bases for individual models are small, and it also leads to a high level of difficulty in assigning a given deposit to a model type, a much higher probability of making errors with regard to the correct genetic interpretations, and a great deal more uncertainty in the application of probabilistic models.

SELECTED ISSUES

1. How do we allow for the existence and eventual discovery of heretofore unknown (in grade, mineralogy, geologic setting) deposit types?
2. How many models are there? How many should there be? When does one stop splitting (or lumping)?
3. How should the models be classified?
4. Who decides, and when, that a model is to be revised or replaced? How do we deal with alternative interpretations for the same deposit?
5. Mineral deposit models are based for the most part on the rare occurrences that develop into mines. How representative are such models of the whole spectrum of mineral occurrences? This issue is particularly critical with grade and tonnage models.
6. To what extent can all deposit types be treated similarly; i.e., can bauxitic laterites, magmatic chromite, sylvite-bearing evaporite, unconformity uranium deposits, epigenetic sulfides in salt domes, skarns around porphyry coppers, and Carlin-type gold deposits all be assessed via the same philosophy? Is it necessary to devise alternative strategies for well-understood deposits (such as gold placers) relative to poorly understood types (such as Mississippi Valley ores) or well understood but difficult predictable deposits (such as diamond-bearing kimberlites)?
7. Are there serious disadvantages to a genetic-descriptive hybrid model?
8. How does the assessor evaluate the future technology or regulations in deciding how to deal with factors such as stripping ratios, dips of veins or beds, or susceptibility of the ore body for in situ mining?

9. How does one define the tectonostratigraphic terrane characterizing a deposit formed amid several major features? For example, the Arizona porphyry copper deposits are made (were once anyway) economic by (1) Tertiary enrichment of (2) Laramide porphyry hydrothermal systems that intruded (3) crational sediments overlying to a (4) Protero-subduction zone. What tectonostratigraphic element is important?

DISCUSSION GROUP 4

EXPERT SYSTEMS (AI): A LINK TO ECONOMIC AND POLICY ISSUES

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Handing off resource assessments to engineers, economists, and policy analysts is like passing money to a customer through the bank window. After you have agreed on the currency and made the transaction, you have little control over how the customer spends the dough. This discussion group is going to focus first on the currency, namely, whether resource assessments should be in the form of "blob maps" and (or) estimates of location, number, size, and grade of undiscovered deposits and second, the ways expert systems can aid in making resource assessments.

Resource assessment is a difficult task. It involves the integration of diverse geologic data, knowledge about mineral deposits, past discoveries, and current engineering and economics. In making an assessment, there are no fixed rules, and, for this reason, it is generally agreed that a high level of expertise is required at each step in the process.

Most current expert system applications, however, are based on a classification scheme; that is, which of the several kinds of deposits in the expert library is the ground in question most like? What is needed by the resource assessment users is either better blob maps or information on where, how much, and how good. This commonly is presented as location, number, size, and grade. The expert system that most closely approaches the second goal might be the one developed by DeVerle Harris for sandstone-hosted uranium deposits. Our question is, "How can we develop more models like that one, and what is standing in the way?"

One controversy is the role of an expert system as either one of two extremes, an assistant to the geologist or a replacement for the geologist. An analogy can be made to computer-generated contour maps. Not so long ago, geologists did not trust such maps. The computer was trusted only to generate gridded data that was then contoured by hand. In the same way, expert systems might be thought of as tools for the geologist who then is required to estimate number, size, and grade using many sources, including that expert system. In this case, expert systems would need to be shown to be better than (or necessary in addition to) such alternatives as books on genetic models or word of mouth.

The opposite notion sometimes involves an ethical equation: Can we use computers where humans fear to tread? Experts are sometimes unwilling to develop certain quantitative estimates, such as remaining reserves in an active mine. But the same experts are willing to help set up a general computer program that will calculate the remaining reserves and then to supply some of the necessary data. Can we use expert systems to generate numeric estimates where the experts are too uncertain?

The advantages in expert systems include the development of audit trails and a certain amount of discipline. The audit trails mean that resource assessments are somewhat reproducible (give similar answers when the same territory is assessed) and compatible (give similar answers for different areas or assessors so that the numbers can be aggregated). The expert systems also makes implicit judgement about who are the experts. This saves each assessor from having to make that decision.

Achieving the goal of using expert systems to meet the goals stated above includes overcoming the following problems:

1. Reluctance and (or) inability on the part of the experts to define carefully their reasoning and logic.
2. The difficulty of estimating the number of deposits in the expert system.
3. The difficulty and (or) expense of including map information in the expert system.
4. The lack of a good track record in already having developed objective, machine-codable, criteria for the existence of deposits.

SELECTED ISSUES

1. Can metallogenic principles be stated explicitly within a rule-based system?
2. Can expert systems provide a structured approach in estimating the number, size, and grade of undiscovered deposits based on geologic, geochemical, and geophysical data? Can the systems help in producing better blob maps?
3. Are there alternative methods to the Bayes' rule for propagating probability distributions through an inference network?
4. What role might an expert system play in the resource assessment process?
5. What do we do for areas in which there are poor or no analogs?

DISCUSSION GROUP 5

THE MANAGEMENT OF MINERALS INFORMATION

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The acquisition of certain kinds of geoscience information tends to increase exponentially. Other kinds have flatter, more traditional acquisition profiles. In conducting resource assessments of specific areas or regions, we are commonly faced with (1) a paucity of information of certain types; (2) a plethora of information of other types; and (3) an uneven mixture of the two. The problem is to organize, select and integrate the available mix of information to best extract the "critical" elements for the task at hand, without dragging in extraneous, non-critical information. Computer management may be part, but not all, of the answer.

The application of advanced technologies has permitted an explosive increase in geoscience information acquisition, generally "raw data" of certain types. Examples include remote sensing (for example, LANDSAT); airborne geophysics data (high-resolution aeromagnetic, aeromagnetic gradiometer, VLF/EM, multiple-window and integrated radiometrics, and so on); regional geochemistry; seismic reflection and refraction profiling, and so on. Other kinds of information are acquired in traditional, slower, and more selective ways, partly because "quick" technologies are not applicable and partly because the information output is in a processed or interpretive as opposed to raw form. Geologic map data and mineral deposit characteristic data are classic examples.

Traditionally, geologists required to produce resource assessments, particularly in remote areas, have been faced with the problem of too little relevant information to work with. Increasingly, the opposite may be the case; the potentially available information may be overwhelming and lead to difficulties in its effective use in the assessment process, given the time frames and deadlines usually associated with resource assessment requirements. Faced with this problem, a geologist falls back on his internal, intuitive, "cranial" approach to information selection, integration and interpretation. He needs help from outside sources of data management and integration. This help has come largely in the form of movement toward formal, computer-aided data base management systems, either centralized, as in some agencies, or decentralized, as in others (for example, the GSC). This has aided measurably in the organization,archiving and accessibility of data sets, but not necessarily in the effective selection, combination-integration, and application of various kinds of data sets to specific tasks. Herein lies the challenge.

SELECTED ISSUES

1. What are the types (hierarchies) of information sets used in resource assessment? How have they evolved? What are the major changes that have taken place in their utilization? What is a typical mix between project-generated information and archival information (non project-specific)? How is this mix changing? (obviously, this depends on area)
2. What are typical (current) machine-based data sets (for example, mineral deposit data files) and how are they used? How much actual use is made of, for example, index-level machine data systems in resource assessment? In exploration? What is the status of "deep files" (for example, mineral deposit models, characteristics, attributes) and how are they used in resource assessment?
3. How are various data sets integrated and interpreted in resource assessment. Are machine-based compilation and integration, using digitized input and various image enhancement-analysis techniques the answer? What is the (current) capability in this field? How is it likely to evolve? What are the alternatives?
4. Can machines really interpret? What are the roles of AI and expert systems, logic models, and so on, here? What models (mineral deposits) are sufficiently accurate and precise for integration by machine with other data sets? what is the role of the human (interpretative) element? What is the relation between the application of various statistical and mathematical techniques and (1) the type of information required, (2) the integration-interpretation process, and (3) the type of product required?

5. What are the kinds and formats of output required? For resource assessment; for exploration; for input to policy formulations? How much output information do managers/administrators/policymakers need? What are bottom lines?
6. Where are we going?

DISCUSSION GROUP 6

THE INCREASINGLY INTERNATIONAL CHARACTER OF MINERALS ISSUES

PARTICIPANTS: Hermann Enzer (leader), Jan Zwartendyk (reporter), Frederick W. Chandler, John H. DeYoung, Jr., Gordon A. Gross, Norman E. Gunderson, Sherman P. Marsh, A. Thomas Ovenshine

In years past, exploration, development, and production of minerals in third-world countries was often accomplished by expatriot scientists, engineers, and companies. Third-world countries now wish to develop indigenous private enterprise, science, and technology. The transfer of appropriate science, technology, and business practices to such countries is hampered by the need for long-term training, lack of established institutions, and an inability in the developing countries to "leap frog" decades of experience in research, exploration, and investment.

To avoid disruptions in the supply of the so-called critical and strategic minerals, it is in the interest of the United States and Canada to promote the discovery, development, and production of such minerals in third-world countries through foreign assistance, cooperative agreements, transfer of technology, and a flow of investment. Concern for the transfer of technology related to management of minerals information and exploration for economic deposits has been a significant aspect of U.S. and Canadian policy since before 1950. Science by its nature is traditionally international, and technology has become increasingly so. Emphasis on the further transfer of an institutional foundation, technological infrastructure, and Western business principles should be to the mutual advantage of participating countries.

SELECTED ISSUES

1. What are the present goals of international cooperation in minerals science, technology, and investments? Are these goals suited to the future needs of cooperating countries?
2. Can existing institutions in the United States and Canada be better used to attain goals, develop policies and programs, improve communications, and facilitate actions toward the goals?
3. Are there major obstacles to improved international cooperation in matters of science, technology, and investment climate?
4. Should institution building in developing countries be a major goal for the United States and Canada? How should institution building be accomplished?
5. Is long-term training of developing country scientists, technicians, and businessmen in Canadian and U.S. institutions the most feasible approach in terms of mutual benefits?
6. What benefits accrue to Canada and the United States as a result of increased science, technology, and investment transfers to developing countries?

DISCUSSION GROUP 7

RECOMMENDATIONS FOR RESEARCH PROGRESS FOR DETERMINING THE PROBABILITY OF MINERAL OCCURRENCE

PARTICIPANTS: Gordon P. Eaton (leader), Robert G. Garrett (reporter), James D. Bliss, C. F. Chung, Lawrence J. Drew, Lyle Harris, Carroll Ann Hodges, W. David Menzie III, Al Miesch, James K. Otton, Norman J Page

Recent advances in regional mineral resource assessment have made the first two steps, delineation of permissible areas by deposit type and estimation of grades and tonnages, solvable, although often quite complicated. Research on the third step, estimation of the number of deposits within delineated areas, has relied on subjective estimates—research on objective estimation of deposit numbers has barely begun.

The goal of such research should be to find ways to provide unbiased, minimum variance estimators of the number of mineral deposits in a region. The estimators should be (1) by deposit type; (2) presented in a probabilistic form; (3) obtained in arbitrarily sized and shaped areas; and (4) consistent with the grade-tonnage estimates.

Some possible approaches include the testing and identification of those individuals who are successful subjective estimators or the calibration of subjective estimators using training sets. Other approaches are to develop base rates (frequency distributions) from well-explored regions or to statistically estimate the probability of occurrence from geologic, geophysical, and geochemical information. The relations among exploration effort and the occurrences, prospects, and grades and tonnages found might provide a useful predictor of the number of deposits.

Research using these or other approaches holds the promise of improving regional resource assessment in two ways: (1) better estimates of the number of deposits will become available, and (2) the research will lead to improvements in the deposit and grade-tonnage models.

SELECTED ISSUES

1. The relation of the probability of occurrence to delineation of permissive areas and to deposit models. How should these parts of resource assessment interrelate?
2. The use of simple occurrence models (frequency distributions) to estimate mineral occurrence. Specific issues might include: (1) What fact should be considered in applying occurrence models, (2) what role should geotechnical information play in these models, (3) what distributions are appropriate and why, and (4) how should scale and spatial effects be considered?
3. The use of multivariate models to estimate mineral occurrence. Specific topics might include: (1) a brief review of the types of multivariate models and their strengths and weaknesses and (2) a discussion of why these models are not more widely used.
4. The use of subjective probability methods to estimate probability of mineral occurrence. Specific topics might include: (1) a discussion of when use of subjective methods is and is not desirable; (2) how to recognize capable estimators; (3) how to train estimators; and (4) can subjective methods and objective methods be linked as in meteorology?
5. The use of other methods, such as geometric probability, to estimate probability of occurrence.

DISCUSSION GROUP 8

ECONOMIC ASPECTS OF RESOURCE ASSESSMENTS

PARTICIPANTS: Brian W. MacKenzie (leader), William D. Watson, Jr. (reporter), Emil D. Attanasi, W. David McRitchie, Gary Morrison, Diane Nielsen, Donald A. Singer, Barbara A. White, John C. Wilson, William Wolf

The purpose of mineral resource assessments is to provide ongoing support for policy and planning in the mineral sector. Thus, regional appraisals of undiscovered mineral deposits are only useful to the extent that the resulting predictions are integrated with broader assessments of the potential value of mineral supply. This necessary integration requires physical assessments of mineral endowment to be combined with appropriate economic specifications and criteria.

The mineral sector may be viewed as a supply process by which minerals are converted from geologic resources to marketable products. Thus, a physical stock of minerals, the total "resource base" or, more specifically, mineral "endowment," flows through a multistage series of mineral sector activities—exploration, development, mining, processing, and transportation—to supply a mineral market. This mineral supply process, created by investment, provides the economic context for mineral resource assessments.

A wide spectrum of resource appraisal methods are available, varying from abstract to applied in terms of usefulness, and from relatively simple to complex in terms of data requirements and analytical procedures. The "resource base: and "endowment" estimates of minerals as a purely physical stock are found at the less-useful end of the spectrum. The estimation of "resources," embodying specific economic and technological conditions, occupies the middle range, comprising a matrix of known-unknown and economic-sub-economic components. Towards the applied end of the spectrum, "potential supply" estimates evaluate the costs, risks, and returns associated with the possible discovery of unknown mineral deposits. This progression of assessments from minerals as a physical stock to minerals as an economic flow demands that increasing attention be paid to economic considerations. Ultimately, mineral resource appraisals play a key role in assessments of the potential value of mineral supply.

SELECTED ISSUES

1. What are the economic elements of mineral resource and potential supply assessments? What economic specifications should be set to satisfy long-term policy and planning needs?
2. Mechanisms for promoting the integration of economic aspects of resource appraisals with geologic, technological, and statistical analysis components.
3. Methods for assessing the potential value of unknown mineral resources in the context of the mineral supply process.
4. Assessing the uncertainty of the potential economic return from undiscovered mineral deposits arising from their size and grade distribution characteristics.
5. The effect of singular discoveries such as Hemlo and Kidd Creek in Canada and Olympic Dam and Broken Hill in Australia on geologic and economic distribution characteristics for all mineral deposits.
6. Defining the "quality" of mineral resources.
7. Estimating time trends in the economic productivity of mineral resources. Is the quality declining?

8. What are the time trends in exploration expenditures per mineral deposit discovered and per unit of recoverable mineral product?
9. How can we separate the economic consequences of depletion on the one hand and advances in geologic concepts and exploration technology on the other?
10. What evidence is there to show whether mineral exploration is a systematic process or a random process?
11. How should the notion of time value be incorporated in resource and potential supply assessments?
12. Effects of location on the competitive position of mineral resources at regional, national, and international levels.
13. Evaluation of discovery risk in exploration and its implications for policy and planning in the mineral sector.
14. Assessment of resource adequacy--the ability of a region or country to meet anticipated consumption requirements to some designated future point in time. What are the associated investment requirements?
15. Evaluating the impact of actual or contemplated government polices on mineral resources and potential supply.

APPENDIX 3.—FIELD TRIP TO POTOMAC GORGE

LEADER: Avery A. Drake

Crystalline rocks of the central Appalachian Piedmont in the Potomac Valley of Virginia and Maryland constitute the Potomac composite terrane of Drake. This composite terrane consists of several terrane fragments that were amalgamated into a stack of thrust sheets outboard of the North American craton during the Penobscotian orogeny (late Cambrian). The composite terrane was subsequently obducted onto the North American craton during the Taconian orogeny (late Middle to early Late Ordovician). Each terrane fragment appears to be underlain by a precursory sedimentary melange that is characterized by fragments of the overlying thrust sheet. The thrust sheet-melange pairs have been termed tectonic motifs.

This field trip will examine some aspects of the Peters Creek-Sykesville motif, the largest terrane fragment within the Potomac composite terrane. The thrust sheet of this motif, the Peters Creek Schist, consists of quartzose schist and metagraywacke. In the Potomac Gorge, the more pelitic parts of the unit record a progressive Barrovian metamorphism from chlorite zone in the west to sillimanite zone and veinitic migmatite in the east. This metamorphism was accomplished about at the aluminum sillimanite forms from both andalusite and kyanite. The high-grade rocks in the eastern part of the Potomac Gorge were later prograde event resulted in the growth of chloritoid and new mica at the expense of retrograde shimmer aggregate. The Peters Creek Schist has experienced several phases of deformation, the latest of which fold the phyllonite fabric.

The precursory melange of the motif, the Sykesville Formation, has a quartzofeldspathic matrix containing fragments of Peters Creek at various metamorphic grades, as well as a variety of exotic rocks including serpentinite.

Quartz veins containing free gold have been mined in the Potomac Gorge. It would be nice to relate this mineralization to the metamorphic-deformational history described above, but it appears to be impossible, because, in 1969, J. C. Reed, Jr., and J. C. Reed (U.S. Geological Survey Bulletin 1286, 1969) presented evidence that these deposits are of Triassic age or later.

This field trip will:

1. Examine the Peters Creek Schist at low metamorphic grade where it is polyphase deformed (type 1 basins and dome interference patterns).
2. Examine the Peters Creek Schist at high (staurolite-kyanite) grade to observe turbite features in metagraywacke.
3. Examine the Peters Creek Schist at very high (sillimanite-veinitic migmatite) grade to observe the development of leucosome (fusion ?) or metamorphic differentiation(?), diabase sills now amphibole, and late cross-cutting granitoid bodies.
4. Examine phyllonitized Peters Creek Schist.
5. Examine the Sykesville precursory melange.

Other stops of opportunity will be made, if time is available.

APPENDIX 4.—SEMINAR ON EXPERT SYSTEMS

LEADERS: Richard B. McCammon and Robert Cheslow

Expert systems have emerged as a practical application of research in artificial intelligence and are among the most exciting new developments in computer science and technology. These programs embody knowledge of a particular application area combined with inference mechanisms that enable the program to use this knowledge in problem-solving situations. The seminar is intended to provide a broad introduction to the concepts and methods necessary for an understanding of how these systems work and, in particular, to demonstrate the PROSPECTOR system, a program that was developed to aid the geologist in evaluating the mineral potential of a site or a region. The current knowledge base of PROSPECTOR consists of the following broad-based classes of ore deposit types:

Sediment hosted

Ancient (Tertiary and older) placer placer Au-U(Th) deposit.
Carbonate-hosted epigenetic (Cu)Pb-Zn(Ag) (manto type).
Carbonate-hosted epigenetic (Cu)Pb-Zn(Ag) (Tintic type).
Carbonate-hosted stratabound Pb-Zn deposit.
Dolomite-hosted copper (Ruby Creek) deposit.
Greywacke-turbidite Zn-Cu-Pb(Hg Fe S) deposit.
Iron-formation
Iron-stone deposit
Lacustrine or cutoff marine basin.
Shale-hosted evaporite (plus oil shale) deposit.
Modern (Quaternary) placer (Au-Th-diamond) deposit.
Restricted marine basin shale-hosted Cu-Pb-Zn (Ag U V) (Kupferschiefer) deposit.
Roll-front uranium deposit
Sandstone-hosted Pb deposit
Shallow marine rift shale-hosted Zn-Pb(Ag)-Cu deposit.
Southern Appalachian Valley carbonate-hosted Zn deposit.

Volcanic hosted

Cyprus-type massive sulfide deposit.
Epithermal bulk Ag deposit.
Superior-type massive sulfide deposit.

Felsic intrusive sourced

Granite porphyry molybdenum (Climax type) (stockwork molybdenum, type 1) deposit.
Porphyry copper deposit
Quartz monzonite porphyry molybdenite (stockwork molybdenum, type 2)
Tungsten skarn deposit

Participants are encouraged to bring maps, data, or reports on areas that may contain one or more of these deposit types in order to compare their results with those using PROSPECTOR.

Beyond PROSPECTOR is the need to develop map-based expert systems for regional mineral resource assessment. A prototype system applied to the White Mountain Wilderness area in New Hampshire will be demonstrated. In this system, regions are evaluated based on the integration of geologic, geochemical, and mineral occurrence data.

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